Prem Lal Kashyap · Vikas Gupta ·
Om Prakash Gupta · R. Sendhil ·
K. Gopalareddy · Poonam Jasrotia ·
Gyanendra Pratap Singh *Editors*

New Horizons in Wheat and Barley Research

Crop Protection and Resource Management

Springer

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Preface

In the realm of food grains, wheat and barley are much pertinent and accredited as a durable mainstay in safeguarding global food and nutritional security. To meet the future needs of burgeoning population, the production and productivity of these crops require a steady growth in a sustainable manner without harming the natural resources as well as protection of these field crops from various biotic and abiotic vagaries. Unfortunately, the current scenario of global trade and climate change has made these crops more vulnerable by an upsurge in outbreaks of transboundary diseases like rusts, Karnal bunt, wheat blast and emergence of new strains as well as diverse types of insect pests in addition to soil health deterioration, increased salinization and alkalinity, nutrient imbalances, low soil organic matter contents, monocropping pattern, water scarcity, emergence of problematic weeds, etc. In this context, the present book *New Horizons in Wheat and Barley Research: Crop Protection and Resource Management* squirreled fragmentary and advanced cutting-edge research innovations in crop protection and agronomic practices along with conservation of natural resource in the form of a book that outlines the path for sustainable production of wheat and barley in a universal and integrated manner. This book volume brings together 88 research experts to offer a novel, practical, up-to-date research progress on pathology, entomology, and resource management of wheat and barley crops in three different parts. The first part of this volume contains eight chapters and provides authoritative, up-to-date, and comprehensive coverage of research progress on major diseases such as rust, smuts, bunts, powdery mildew, and foliar blights. This part also explores a multitude of developments in disease forecasting, antimicrobial agents, and integrated disease management of principal wheat and barley diseases of global significance. The second part of this volume contains four chapters and highlights the research progress in understanding the biology and integrated management of insect pest and nematode problems of wheat and barley crops using recent interventions of genomics and nanotechnology. In addition, this part also provides deep insights into the technological innovations for post-harvest management of insect pests in food grains. Finally, the concluding part of the book contains nine chapters and delivers the latest glimpses of technological needs and resource optimization in wheat and barley production system along with frontier mechanization technologies, improved precision agronomic, pluralistic extension and policy interventions for enhancing the resource use efficiency and livelihood security of the farmer in the era of climate smart wheat and barley farming. This part also highlights the agroforestry-based cropping systems, integrated weed management strategies, and innovative pathways to increase the nutrient use efficiency for sustainable food production.

It is assumed that the eagerness, enthusiasm, and remarkable opportunities presented in this work will enlighten graduate and postgraduate students, academicians, scientists, and researchers at universities, institutes, industries, and government organizations, as well as policy makers and research beginners with inclusive and succinct insight about the basic and applied perspectives of wheat and barley protection and resource management. This book will inspire readers to push the field forward to new frontiers to make quality food more accessible than ever before in a sustainable manner and to meet the needs of the global growing population in the era of climate change. We thank all the eminent authors and acknowledge their valuable contributions towards publishing this quality book.

Karnal, India

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Contents

Part I Paradigm Shifts in Disease Management

1 **Wheat Rust Research-Shifting Paradigms Globally** 3
Subhash C. Bhardwaj, Om P. Gangwar, Pramod Prasad, and Subodh Kumar

2 **Forecasting of Wheat Diseases: Insights, Methods and Challenges** 21
Jaspal Kaur, Ritu Bala, and Parminder Singh

3 **Leaf Blight Disease of Wheat and Barley: Past, Present and Future** 77
Sudhir Navathe, K. J. Yashavanthakumar, Ajeet Kumar Pandey, Ravindra M. Patil, Vijendra S. Baviskar, and Ramesh Chand

4 **Smut and Bunt Diseases of Wheat: Biology, Identification, and Management** 107
Antul Kumar, Anuj Choudhary, Harmanjot Kaur, S. K. Aggarwal, and Sahil Mehta

5 **Powdery Mildew of Wheat: Research Progress, Opportunities, and Challenges** 133
Vijay Rana, Aashima Batheja, Ravi Sharma, Amit Rana, and Priyanka

6 **Antimicrobial Agents for Wheat Disease Management: Mode of Action and Its Application** 179
Sunita Mahapatra, Sunanda Chakraborty, Pravallikasree Rayanoothala, Srikanta Das, Santosh Kumar Bishnoi, and Sudheer Kumar

7 **Integrated Management of Barley Diseases: Current Status and Future Research Priorities** 215
Pradeep Singh Shekhawat, Shiv Pratap Singh, and Styapal Bishnoi

8 **Viral Diseases of Wheat: Research Progress and Future Perspectives** 261
Promil Kapoor

Part II Innovations in Entomology and Nematology Research

9 Biology and Management Strategies of Major Insect-Pests of Wheat 283
Poonam Jasrotia, Beant Singh, and Mohini Nagpal

10 Technological Innovations for the Management of Insect-Pests in Stored Grains 309
Rakesh Kumar Gupta, Mushtaq Ahmad Guroo, Mudasir Gani, Kamlesh Bali, and Ramandeep Kour

11 Modern Approaches for the Management of Cereal Cyst Nematodes in Wheat and Barley 321
Manoranjan Dash, Amit Ahuja, Uma Rao, and Vishal Singh Somvanshi

12 Nanotechnology for Wheat and Barley Health Management: Current Scenario and Future Prospectus 337
Prem Lal Kashyap, Sudheer Kumar, Noyonika Kaul, Sumit Kumar Aggarwal, Poonam Jasrotia, Ajay Kumar Bhardwaj, Ravindra Kumar, and Gyanendra Pratap Singh

Part III Expanding Horizons in Resource Management

13 Integrated Management Practices for Incremental Wheat Productivity 367
B. S. Mahapatra and Prithwiraj Dey

14 Improved Agronomic Practices for Enhancing the Resource Use Efficiency and Productivity of Wheat and Barley 393
Rajender Singh Chhokar, Neeraj Kumar, Ramesh Kumar Sharma, Subhash Chander Gill, Ajit Singh Kharub, Anil Kumar Khippal, and Subhash Chander Tripathi

15 Efficient Irrigation Water Management in Rice-Wheat Cropping System 427
Raj Pal Meena, H. T. Sujatha, Neeraj Kumar, Karnam Venkatesh, and S. C. Tripathi

16 Fertilizer Consumption in Wheat Production Systems: Trends and Policies 453
K. V. Praveen and K. S. Aditya

17 Technical Efficiency in Indian Wheat Production: Regional Trends and Way Forward 475
Ankita Kandpal, T. M. Kiran Kumara, R. Sendhil, and S. J. Balaji

18 Frontier Mechanization Technologies for Wheat Based Cropping Systems 491
Neeraj Kumar, R. S. Chhokar, S. C. Tripathi, S. C. Gill, and Manoj Kumar

19 Innovative Pathways to Increase Resource Conservation and Nutrient Use Efficiency in Rice-Wheat Cropping Systems for Food Security and Decreased Environmental Footprints 511
Ajay Kumar Mishra, Shiveshwar Pratap Singh, Rajeswari Das, Vandana Kumari, Sarita Mishra, Sheetal Sharma, and Subhra Sahoo

20 Integrated Weed Management in Wheat and Barley: Global Perspective 545
Ankur Chaudhary, Rajender Singh Chhokar, and Samunder Singh

21 Agroforestry for Sustainable Cereal Based Cropping Systems in Indo-Gangetic Plain Region 617
Asha Ram, Atul Dogra, Inder Dev, Naresh Kumar, Kamini Gautam, Sunil Londhe, A. K. Handa, Ramesh Singh, A. Arunachalam, and S. K. Dhyani

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Prem Lal Kashyap is working as a senior scientist in the area of plant pathology at ICAR-Indian Institute of Wheat & Barley Research, Karnal, and has ten years of research experience. He had his agricultural education from Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya (CSKHPKV), Palampur, and Punjab Agricultural University (PAU), Ludhiana (Punjab). He has made an outstanding and pioneering contribution in the area of phytopathogenomics, biomarker development, biocontrol, and integrated disease management. He identified five new chemical molecules for the management of wheat diseases and pests; reported five new races of yellow rust of wheat and contributed to the development of "GEHOON DOCTOR" mobile app. He decoded whole genome of several agriculturally important microorganisms, developed biomarkers for early and precise diagnosis of plant pathogens (*Alternaria*, *Fusarium*, *Colletotrichum*, *Tilletia indica*, *Urocystis agropyri*, *Puccinia triticina,* etc.), and developed a formulation "Biogrow" available for commercialization by Agrinnovate (ICAR) India. He has three wheat varieties to his credit and has filed two patents. Dr. Kashyap has contributed immensely in resource generation through externally funded projects from DBT and other agencies of Indian Government. He also created a large pool of trained human resource in the area of plant pathology that has enabled successful product development following his approach. He has more than 150 publications to his credit, including 70 peer-reviewed research papers, 6 books, 30 book chapters, 40 popular articles, and 6 technical manuals. He has visited several countries including the USA, Kenya, Mexico, Bangladesh, and Bolivia for academic pursuits. For significant research contribution in the field of agricultural sciences, Dr. Kashyap has been recognized with several prestigious awards including NAAS Associateship-2019, NAAS Young Scientist Award, Dr. Basant Ram Young Scientist Award, Prof. Abrar Mustafa Memorial Award, M. K. Patel Memorial Young Scientist Award, and Prof. Mahatim Singh Memorial Award.

Vikas Gupta is a wheat breeder at the ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana, India. He received his agricultural education from Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu (J&K), CCS University, Meerut (UP), and Punjab Agricultural University Ludhiana (Punjab). His areas of interest include resistance breeding, biofortification, and input use efficiency. As a wheat breeder, he has developed eight wheat varieties which have been released for cultivation in different zones of the country. Dr. Gupta has developed the first biofortified bread wheat variety, WB 2 (Av. yield 51.6q/ha), having high grain zinc and grain iron contents with a view to deliver micronutrients through wheat grains. Apart from that he had developed and registered more than 15 genetic stocks for different traits of agronomic importance. Dr. Gupta also identified QTLs for Karnal bunt, spot blotch, and grain zinc content in wheat based on genome-wide association mapping studies which are amenable to molecular breeding. Dr. Gupta worked as visiting scientist in the Dept. of Crop and Soil Sciences at Washington State University Pullman (USA) in 2015 and also in the International Maize and Wheat Improvement Center, Mexico, in 2018. Dr. Gupta has published many scientific articles in international and national journals of repute, book chapters, popular articles, and technical bulletins.

Om Prakash Gupta received his M.Sc. and Ph.D. from Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, and ICAR-Indian Agricultural Research Institute (IARI), New Delhi, respectively. He is presently working as scientist (Plant Biochemistry) at ICAR-Indian Institute of Wheat and Barley Research (ICAR-IIWBR), Karnal. Dr. Gupta has more than 10 years of research experience in the area of plant biochemistry and molecular biology and has significantly contributed to deciphering the role of small RNA during various biotic and abiotic stresses, biofortification, marker development, nutritional and processing quality, etc. He has co-developed three genetic stocks and one bread wheat variety suitable for various quality traits.

Dr. Gupta has been bestowed with more than 80 publications to his credit which include 30 research and review papers, 20 book chapters, 4 books, and 30 popular articles. He presented his research papers in several national and international symposia/workshops/conferences. He has immensely contributed to resource generations through several externally funded projects funded by Indian agencies like DBT and DST, and International agency including CIMMYT. Dr. Gupta is also involved in teaching Fundamentals of Molecular Biology course to Ph.D. students. Due to his immense research contributions, Dr. Gupta has been serving as editorial board members and reviewers of many international journals. Due to his outstanding contribution in research and meritorious profile, Dr. Gupta has the distinction of receiving numerous honors, fellowships, and awards in recognition of his excellent academic and research contributions. He is fellow of the Society for Advancement of Wheat and Barley Research (SAWBAR) and received several awards including Jawaharlal Nehru Award for outstanding Doctoral thesis by ICAR, University Silver Medal, Aspee Gold Medal, Dr. Kirtikar Memorial Gold Medal, and Chowdhary Charan Singh Memorial Award during his bachelor degree program.

R. Sendhil presently serves as a scientist at the ICAR-Indian Institute of Wheat and Barley Research under the aegis of Indian Council of Agricultural Research. He holds about 14 years of experience in R&D and published around 85 research papers in peer-reviewed national and international journals. Sendhil has handled more than 10 research projects in various capacities and presented research findings in several national and international forums including the annual professional society meetings. His research interest includes food and nutrition security, value chain development, climate change, market outlook, impact assessment, and technology policy. He is committed to his professionalism and honored with several recognitions including the Lal Bhadur Shastri Outstanding Young Scientist (ICAR), Fellow (SAWBAR), Prof. Mahatim Singh Memorial Award (SAWBAR), Best Worker (IIWBR), Uma Lele Mentorship Award (AAEA), NFP grant (NUFFIC), LI-LMI AAEA Award, IARI Fellowship, and ICAR-JRF. Hitherto, he completed seven research projects and continuing with three projects. Apart from research, he is into teaching and mentoring M.Sc. & Ph.D. scholars at the ICAR-National Dairy Research Institute, Karnal. His interest largely focuses on multidisciplinary and multi-institutional research and learning, fostering innovations and policy formulation leading to agricultural transformation, especially under the wheat and barley production system.

K. Gopalareddy Scientist (Genetics and Plant Breeding), serves in the ICAR-Indian Institute of Wheat and Barley Research, Karnal, under the aegis of Indian Council of Agricultural Research since 2015. His contribution towards the development of wheat varieties and genetic stocks is commendable. Dr. Reddy was involved in the development of seven wheat varieties and 15 genetic stocks to benefit multitude stakeholders including farmers, consumers, researchers, and industry. His research is largely focused on the development of high yielding wheat varieties with improved quality attributes. He utilized modern breeding tools like genomic selection, MARS, MAS, and GWAS to dissect complex traits in wheat. He also involved in five externally funded projects, majorly focusing on wheat quality improvement. He published research and review articles of national and international repute, book chapters, technical bulletins, extension leaflets, and popular articles.

Poonam Jasrotia has more than 12 years research experience in the field of Agricultural Entomology. She is currently working as a Principal Scientist in the Cop Protection Division of ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana, India. Her research work mainly focuses on exploring the mechanism and basis of aphid resistance in wheat and barley crops and to identify the aphid-resistant novel germplasm for crop varietal improvement program. Besides, her other research project is based on the development of botanical-based alternatives for management of stored grain pests of wheat and barley crops. Her past research projects were dominantly related to studying insect behavior of sucking insect pests; thrips, mealybugs, and aphids to develop management strategies that limit damage to agricultural crops and provide ecosystem services. Dr. P. Jasrotia has diverse experience of working in international organizations such as Agricultural Research Organization (ARO), Volcani Center of Israel, North Carolina State University, Raleigh, USA, and Great Lakes Bioenergy Research Center at Michigan State University, MI, USA. As Sustainability Research Co-ordinator for Great Lakes Bioenergy Research, she carried out climate change-related research on insect biodiversity, biogeochemistry, greenhouse gas emissions, and water balance in the potential biofuel crops. She has published more than 40 research publications in high-impact journals.

Gyanendra Pratap Singh ICAR-Indian Institute of Wheat and Barley Research, Karnal, has more than 27 years of agriculture research experience including 10 years of teaching and 4 years and seven months of administration experience, which led to many milestones. Dr. Singh is instrumental in the development of 51 wheat (5 biofortified varieties) and 03 barley varieties and 01 potato variety benefitting many farmers, consumers, and industries. He is the main force behind the development and fast spread of improved wheat technologies including DBW 187, DBW 222, HD

2967, HD 3086, and DBW 173 as these are readily adopted by farmers as evident from top breeder seed indent and also a large number of licensing through institute's business incubation model. Dr. Singh largely focuses on intrinsic research on heat and drought tolerance for wheat improvement in India and developed many climate resilient wheat varieties. He is also the leader of cutting-edge technologies like Marker Assisted Recurrent Selection and Precision Phenotyping for heat and drought tolerance. He has published more than 200 research articles of national and international repute with high-impact factors, 14 books, 65 book chapters, 57 technical bulletins, 55 popular articles, and 05 Policy/Strategy papers.

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Part I

Paradigm Shifts in Disease Management

Wheat Rust Research-Shifting Paradigms Globally

1

Subhash C. Bhardwaj, Om P. Gangwar, Pramod Prasad, and Subodh Kumar

1.1 Introduction

Many biotic and abiotic factors impede the efforts to increase wheat production worldwide. Among the biotic constraints, rusts are the major obstacles in wheat production. Wheat rusts have been devastating pathogens since time immemorial. There are records of their occurrence as early as 1300 BC (Kislev 1982). Even in the modern literature these have been categorized as historic pathogens, capable of causing huge losses to wheat crop worldwide (Stakman and Harrar 1957). Leaf rust (*Puccinia triticina*), stem rust (*P. graminis* f. sp. *tritici*) and stripe rust (*P. striiformis*. f. sp. *tritici*) are wheat diseases of global importance. The epidemic losses caused due to rusts on wheat are the interplay of susceptible host, virulent pathotypes of rust pathogens, favourable environment, time duration and human indulgence (Fig. 1.1). Among these factors, matching virulences of rust pathogens, susceptible wheat cultivar, stage of crop and favourable environment are the key factors in causing epidemics. The stage of wheat crop at which the infection occurs is very crucial. The early infections lead to more loss than late ones. The stage of wheat crop is also important because the adult plant resistance is triggered after the third leaf formation. Thus, a variety which is susceptible in initial stages could become resistant later on. This is one of the reasons that wheat rust epidemics have become infrequent, as many unknown adult plant resistance genes have conferred field resistance to rusts.

Among the wheat rusts, leaf (brown) rust is the most common, occurring mostly on the leaves, leaf sheaths, leaf blades and spreads well if the temperature ranges from 10 to 30 °C. Losses to wheat due to leaf rust can be up to 50% (Anonymous 1982). Leaf rust occurs throughout the wheat-growing areas in the world. Stem

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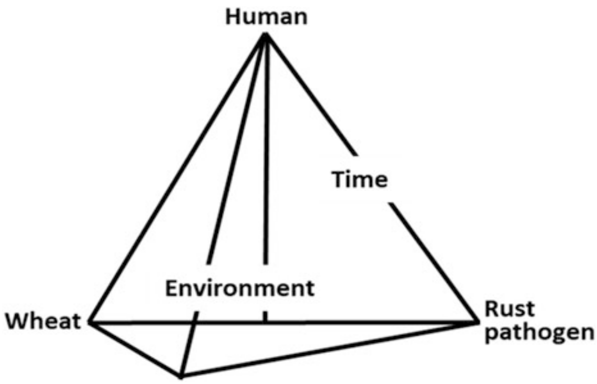

Fig. 1.1 Variables of wheat rust epidemics

(black) rust of wheat generally occurs on stems, leaf sheaths and sometimes on leaves. It is favoured by warmer wheat-growing situations (15–35 °C) in the world and occurs in central and peninsular India. It appears late in the season; therefore, it is not a problem in the Northern hills zone, Northwestern and Northeastern India. Stem rust can cause up to 100% loss on susceptible wheat varieties. Stripe (yellow) rust of wheat is mainly a disease of cooler areas (2–15 °C); however, recently high temperature (up to 20 °C) loving stripe rust cultures have been observed in many countries. In many cases, the crop losses due to wheat stripe rust can be severe (50%) and under extreme epidemic conditions, it can lead to 100% losses (Roelfs et al. 1992). In India, wheat stripe rust is a major problem of Northern hills zone and Northern plains zone.

Wheat rusts have principally remained under control for quite some time, and largely it was thought that these have been managed. However, occurrence of *Yr*9 virulences in Syria, Iran in 1990, 1992 and 1993 caused severe stripe rust epidemics in Western Asia had sent alarming bells. In April 1994, the *Yr*9 virulences rendered Veery#5 cultivars such as Pak81, Pirsabak85 and Seri82 susceptible in the NWFP of Pakistan (Nagarajan and Saari 1995). Subsequently, *Yr*9 virulences have created havoc in China, the United Kingdom, Africa and other parts of the world. In India, virulences on *Yr*9 appeared in 1996 and 2001 (Prashar et al. 2007). Later on, the occurrence of *Sr*31 virulences also called Ug99 in Uganda during 1998 (Pretorius et al. 2000) caused an international concern. It rendered gene *Sr31* ineffective after its use for about four decades. Consequently, about 40% of world's wheat material came under the threat of stem rust epidemic (Singh et al. 2011). During the last decade, 13 pathotypes in the lineage of Ug99 have been identified from 13 countries (CIMMYT 2019).

These events have reminded us of the adage of Dr. Norman Borlaug, 'Rust never sleeps'. There is always a continuous race for supremacy between wheat breeders and rust pathogens. Breeders develop new wheat varieties, whereas rust pathogens evolve new pathotypes/virulences which render resistant varieties susceptible. New virulences evolve through either sexual reproduction (in areas or countries where alternate hosts are functional) or mutations and somatic hybridization (where alternate hosts are not functional). Mutation is a very common mode of evolution of new pathotypes especially when alternate hosts are non-functional. Virulence genes are mostly recessive. Recessive mutations are more frequent than the dominant ones. Frequency of recessive mutations is about 1×10^{-5}–110^{-6}. The wheat rusts being dikaryotic would require a double mutant of the order of 1×10^{-10}–1×10^{-12}. The urediniospores are produced in trillions, and therefore the probability of occurring a mutant and resultant infection on a previously resistant cultivar carrying single gene for resistance is very high. This phenomenon leads to the susceptibility of wheat varieties and succumbing of vertical resistance genes (Knott 1989) popularly called boom and bust cycle.

Hence, efforts of the scientists are required to remain few steps ahead of the pathogen. Therefore, a continual vigil on wheat rusts is required. Monitoring of pathotypes in early stages and evaluation for rust resistance, pre-emptive breeding and strategic deployment of wheat varieties using pathotype zonation have now become integral part of wheat rust management system (Bhardwaj et al. 2019). With the landmark invention of Craigie (1927), demonstrating the role of pycnia in the life cycle of stem rust fungus, our understanding of wheat rust fungi has increased. The transition from simple to refined science over these 100 years has been described on the succeeding pages.

1.2 Detection and Diagnosis

Precise diagnosis of plant diseases or detection of the pathogens causing these diseases is a pre-requisite for employing effective management strategies. Traditionally, wheat rusts are being diagnosed based on the symptoms and signs of these diseases on wheat. The characteristic symptoms of wheat rusts are as follows: (1) Stem rust: symptoms appear as small-brownish coloured pustules lower leaves and stem at early stages of infection. The urediospores are oval (25–30 μ × 17–20 μ approximate) in size. As the disease progresses, the pustules become larger and form lesions of dark-brown colour. Towards the end of the disease cycle, dark black coloured teliospores (40–60 μ × 15–20 μ approx.) are produced. (2) Leaf rust: at initial stage the disease or symptoms appear on leaf blade as light orange colour round to oval (0.5–2.3 mm approx.) pustules. Later on, these pustules appear in partially yellow brownish colour. At the advanced stage, the pustules turn brown. (3) Stripe rust: in case of stripe rust, the uredia are mostly linear, citron orange to yellow colour and typically narrow to form stripes on the leaves. The uredospores developed in case of stripe rust are round to ovate in shape (25–35 μ × 20–35 μ approx.). The disease appears on leaf, leaf sheaths, awns, etc. Diagnosis of these pathogens becomes slightly difficult when the symptoms of two or more wheat diseases including rusts are merged together. Another approach to diagnose these diseases is through the use of molecular markers, which have been utilized for precise forecasting of disease outbreak. Molecular markers could be utilized for estimating the initial inoculum load of the pathogen, and therefore, prophylactic disease control practices could be placed well before the occurrence of a disease outbreak. Molecular marker-based diagnostic assays have been developed for the early detection of *Puccinia* spp. causing wheat rusts (Aggarwal et al. 2017; Lihua et al. 2008; Liu et al. 2014).

A range of image-based approaches assimilating image acquisition and analysis are described to have massive prospects for accurate disease diagnosis. These approaches include thermal, chlorophyll fluorescence, multispectral, hyperspectral and RGB (red, green and blue)-based sensors, some of which (hyperspectral imagery) have been utilized for wheat rusts' detection. Performance of ten spectral vegetation indices was evaluated for the identification of yellow rust infection on wheat leaves (Devadas et al. 2009). Likewise, diverse wheat rust diseases were detected based on hyperspectral measurements of vegetation indices. Some of the indices were able to successfully detect yellow rust infection (Ashourloo et al. 2014). Automatic embedded image processing system was developed for the detection of *Puccinia triticina* and grading disease diagnosis (Xu et al. 2017). These image-based approaches could be further customized and utilized as agricultural robot to inspect, diagnose and classify crop diseases in the field.

1.3 Variability in *Puccinia* Species on Wheat

A resistant wheat variety becomes susceptible after a few years of its cultivation. The detailed investigations of this cause have led to the identification of variants in a rust pathogen named races or pathotypes. Many scientists have used these terms interchangeably. Pathotype is a subdivision of a species or a *forma specialis* distinguished by common characters of pathogenicity or symptoms produced on varieties (differentials) of a host. Pathotype is used to describe the type (reference) culture of a pathovar. A list of 294 races of *P. graminis tritici* was given by Stakman et al. (1962). Likewise, an updated list of 226 variants in *P. triticina* was published by Johnston and Browder (1966) and 66 of *P. striiformis tritici* by Johnson et al. (1972). However, with the propounding of gene for gene hypothesis by Flor (1956), it was realized that pathotype identification systems are not on sound footings. Subsequently, pathotype identification systems based on Near Isogenic Lines (NILs) were put in to practice in different countries. The pathotype identification systems followed by various countries are different. Huerta-Espino et al. (2011) have discussed the systems for naming pathotypes of *P. triticina* being followed world over. There was a move internationally to have a common system for the identification of pathotypes of *Puccinia* spp. on wheat. However, it did not materialize. The main reason for the disagreement was differences in populations of various regions/countries. Few genes are effective in one but are ineffective in other countries. Therefore, common differentials for the identification of pathotypes could not come into existence. Consequently, different countries generally follow different differentials or identification systems. However, it is easy to decode every system and know the population structure of any country by knowing the avirulence and virulence structure of pathotypes.

1.4 Shifting Virulence Patterns in Population of *Puccinia* Spp. on Wheat

Wheat and rusts have coexisted and coevolved together for centuries. More variability and advanced populations of rust pathogens have been seen either around the centres of origins or in areas where more vibrant and dynamic wheat breeding programmes are going on. The evolution of rust pathogens is independent of wheat. However, a resistant wheat variety favours the selection of a virulent mutant. Introgression of new genes is countered easily by the wheat rust pathogens. Even the transgenic varieties developed through 1B.1R translocation, *Lr24/Sr24*, and many more were rendered susceptible, shortly after their commercialization. In some cases, virulent pathotypes of rust pathogens have evolved even before a wheat variety based on the corresponding resistance was developed or commercialized. Incorporation of a new resistance gene is easily matched by the dynamic rust pathogens. Consequently, the pathogen acquires virulence every time with one step gain in virulence and we are heading towards super races (Bhardwaj et al. 2019). Breeders have been called inciters of epidemics (Johnson 1961). Replacement of wheat varieties is readily coped up with the shift in virulence patterns and building up of matching pathotypes. Therefore, frequent shift in virulence patterns is a common phenomenon in wheat rust pathogens. The rapid increase in *Yr9* virulent pathotypes in NWPZ of India was due to the cultivation of PBW343 with unique resistance and clean foliage. A distinct shifting virulence pattern can be seen in stripe rust pathogen as new pathotypes have emerged almost every 5–6 years in northern parts of India (Prashar et al. 2007; Gangwar et al. 2017). The wheat cultivar PBW343 was released in 1995, adopted quickly by farmers of Punjab where it occupied more than 90% wheat area of this state, and about seven million ha area throughout the Indo-Gangetic Plains (Singh et al. 2017). Subsequently, a new pathotype 78S84 emerged in 2001 with matching virulence to PBW 343, and this pathotype became predominant.

Cultivation of PBW 343 had to be discontinued due to the build-up of pathotype 78S84 of *P. striiformis*. Later on, PBW343 was replaced with a number of wheat varieties, and pathotype 78S84 was replaced by 46S119. In 2014, three new pathotypes 110S119, 110S84 and 238S119 which possessed combined virulence to Strubes Dickkopf and Suwon92xOmar were detected (Gangwar et al. 2019), and now 238S119 has become most prevalent. It was observed that with the emergence of new pathotypes, old pathotypes get replaced due to the cultivation of new wheat cultivars which guide shifts in pathogen's virulence patterns. Competitive ability and fitness potential decide the predominance of pathotype as we have seen it in the case of different pathotypes of *Puccinia triticina* (Bhardwaj et al. 2014a; Gupta et al. 2018).

1.5 Alternate Hosts for Wheat Rust Fungi

It is well known that in off-season, wheat rusts complete a part of their life cycle on the alternate hosts. Prior to 2010, alternate hosts were not known for *P. striiformis*. In a landmark discovery, Jin et al. (2010) could prove that *Berberis chinensis, B. koreana, B. holstii* and *B. vulgaris* are alternate hosts for wheat yellow rust fungus. Later on, in China too, susceptible *Berberis* spp. were found which may facilitate in sexual cycle of *P. striiformis* f. sp. *tritici* and contribute to the diversity of the fungus (Zhao et al. 2013). The leaf rust pathogen (*Puccinia triticina*) completes its sexual life cycle on alternate hosts like *Thalictrum* spp., *Isopyrum fumarioides*, *Clematis* spp. and *Anchusa* spp. (Jackson and Mains 1921; de Olievira and Samborski 1966). *Berberis*, *Mahonia* and *Mahoberberis* are the alternate hosts of *Puccinia graminis* f. sp. *tritici*. However, under Indian conditions, none of the alternate hosts is functional; therefore, fungus perpetuates as mycelia or uredial stage only. Consequently, we reinvestigated the role of alternate hosts in the life cycle of wheat rusts in India. Inoculations of aeciospores from *Berberis* spp. growing in Himachal, Uttarakhand and Nepal did not cause any infection on the wheat leaves. Therefore, in the absence of alternate hosts, drawing a parallel on survival of *Puccinia* spp. on grasses, it was concluded that wheat rusts remain dormant in some collateral, unknown alternate or some unknown hosts and produces infectious spores when the environment becomes favourable (Bhardwaj et al. 2019).

1.6 Epidemiology of Wheat Rusts

Alternate hosts play a definite role in the epidemiology of wheat rusts. However, in countries where *Berberis* spp. do not occur or alternate hosts are non-functional, it is a big question that, how the rusts recur every year? In addition to India, Europe, Australia, New Zealand, South Africa, Ecuador, Pakistan, Nepal, Bangladesh and Bhutan fall in this category. In most of these countries, wheat harvest is followed by harsh summer and in many rainy seasons also. There is no wheat crop in the off-season in many of these nations. Planting of wheat disease monitoring nurseries in Northern India also showed that wheat cannot be the host in off-season. In all the places wheat crop did not survive the rainy season except the one at Shimla. Among the rusts, only leaf rust appears at Shimla every year on disease trap nursery. In India, wheat growing in off-season is limited to wheat rust research centres in Wellington (Tamil Nadu), Dalang Maidan (Himachal Pradesh), very limited area in Kinnaur district of Himachal Pradesh and Ladakh area which do not play much role in the epidemiology of wheat rusts elsewhere in India. The pathotypes occurring in these areas are generally primitive and these do not occur in adjoining plains. In addition, wheat rusts appear in plains first whereas late in the hills. It is also noteworthy that new pathotypes have been observed initially in plains and subsequently 4–5 years later in the hills. Moreover, there is a lag period between harvest in hills and young wheat crop in the plains of India. Thus, the recurrence of wheat rusts every year in India or other countries is an area of future investigations (Bhardwaj et al. 2019).

1.7 Ug99 and BGRI

Wheat stem rust had become a disease of past for about 60 years. Most of the wheat varieties in the initial stages developed at CIMMYT, Mexico and different wheat-growing countries were bred for stem rust resistance. Later on, 1B.1R translocation (*Lr26*/*Sr31*/*Yr9*) conferred resistance to all the wheat rusts. Consequently, stem rust resistance got ignored inadvertently and over-dependence on *Sr31* to manage wheat stem rust occurred. However, in 1998, some of the wheat lines having *Sr31* showed susceptibility to stem rust in Uganda and that led to the identification of Ug99 or the *Sr31* virulence (Pretorius et al. 2000). It was observed to be a threat to wheat cultivation in about 40% of the world's acreage (Singh et al. 2011). The pathogen is very dynamic, evolving very fast and 13 new members have been added to the Ug99 lineage of *P. graminis tritici*. The Ug99 group of variants has been reported from 12 other countries. Another variant PTKSK was detected from South Africa in 2017. This group of races has spread to Kenya, Ethiopia, Yemen, Sudan, Tanzania, Mozambique, Zimbabwe, South Africa, Egypt and Iran (CIMMYT 2019). The risk area of Ug99 type of races could be to the tune of 50 million hectares which is around 25% of the world's area under wheat (Singh et al. 2008). The Indian wheat varieties PBW343, PBW373 and many others also became susceptible to Ug99 type of races and were withdrawn from the cultivation. Over the years, these virulences have moved to other wheat-growing areas. After the report of *Sr31* virulence of *Puccinia graminis* f. sp. *tritici* during 1998 in Uganda, Ug99 was widely publicized as a major challenge to wheat production in India. The detailed analyses of epidemiology of wheat rusts in context to the occurrence of Ug99 in main wheat belt of NWPZ in India have shown that Ug99 cannot be a threat to wheat crop in this zone (Nagarajan 2012; Bhardwaj et al. 2014b) as it has not appeared in this part of the world even after 23 years. Notwithstanding that, taking proactive measures, all the Indian wheat germplasm especially Advance Varietal lines were evaluated in Kenya and Ethiopia regularly. The information thus generated was used for deploying wheat varieties in stem rust-prone areas. These areas of India have almost 100% coverage with Ug99-resistant wheat varieties. Most of the wheat varieties under cultivation in the Peninsular and Central zone have resistance to Ug99 type of virulences.

Considering the circumstances, Dr. Norman Borlaug appealed for a joint international effort to tackle the rust menace. It led to the formation of the Borlaug Global Rust Initiative (BGRI) on September 9, 2005, at Nairobi, Kenya, with the aims to track the movement of Ug99 virulence, evaluate released cultivars and other lines for resistance against Ug99, share the generated information worldwide, and incorporate the seedling and adult plant resistance into acceptable agronomic background. Under the BGRI guidelines, the evolution and migration route of Ug99 group races were monitored so that an early warning system could provide alarms to all stakeholders in case of an epidemic. India has been actively involved in germplasm evaluation against Ug99 group races in Kenya and Ethiopia. As preparedness for combating the likely threat of Ug99, about 250,000 wheat genotypes which included advanced breeding lines from African and Asian countries were tested for resistance to stem rust Ug99 group races at Njoro, Kenya, and Kulumsa and Debre Zeit, Ethiopia during 2005–2012 (Bhardwaj et al. 2014b). Institutions like BGRI, CIMMYT, Kenya Agricultural and Livestock Research Organisation, and Ethiopian Institute of Agricultural Research have imparted training to many researchers of the world on the identification of Ug99-resistant wheat germplasm. Fortunately, gene *Sr31* is still effective against all races of stem rust pathogen occurring in India and adjacent countries. The use of *Lr26/Sr31/Yr9* type of resistance has now come down to 18% from the 40% earlier. Moreover, we are proactive in keeping a vigil over and tracking stem rust pathogen spreads, survey and surveillance, and varietal deployment. Therefore, India has an effective preparedness to tackle such kinds of threats.

1.8 Deoxyribonucleic acid (DNA) Polymorphism and Rust Genome Sequencing

Molecular analysis was performed on Indian pathotypes of *Puccinia triticina* by using SSR markers. High genetic diversity among the pathotypes was observed, and these could be grouped into seven major clusters. These findings offer valuable information for framing suitable disease management strategies through appropriate region-specific gene deployment and improve the understanding of the population biology and evolution of brown rust fungus in the Indian subcontinent (Prasad et al. 2017; Prasad et al. 2018a, b). These investigations also suggest that Indian population of wheat rust pathogens is different from that of other continents.

The genome of *P. triticina* (wheat leaf rust fungus) was decoded to understand the molecular basis of variability in rust fungi. Based on this study, a highly variable *Puccinia triticina* Race77 and its 13 biotypes were compared with a stable Race106. Race106 has not mutated since its first detection in 1930 and preserved at ICAR-IIWBR, Shimla. However, Race77 which was first detected in 1954 from Pusa (Bihar) has evolved into 13 pathotypes (races) and affects wheat production in the country. Therefore, next-generation sequencing technology was used to decode the genomes of these races to understand the molecular basis for fast evolution, virulence and adaptability within Race77, and stability of Race106 genome. A high-quality draft genome sequence (~100 Mb) of Race77 group exhibited 27,678 protein-coding genes responsible for various functions. Genome-wide comparative analysis revealed that 37.49% and 39.99% genomes are repetitive in case of Race77 and Race106, respectively. Race77 is significantly distinct from Race106 at repeat elements, segmental duplication and SNP(Single Nucleotide Polymorphism)/InDel (Insertion or Deletion) levels. Some "hot spot regions" in the genomes of Race77 were located. These were responsible for fast evolution and variability in Race77. This study provided an insight into the genome structure and molecular basis of variation and pathogenicity of *P. triticina.* This information would be an important landmark research and would facilitate wheat improvement programme in India (Kiran et al. 2016). Likewise, the genome of three races (K, 31 and 46S119) of *P. striiformis* f. sp. *tritici* (wheat yellow rust fungus) (Kiran et al. 2017) and four *P. graminis tritici* (stem rust) races were also decoded (Kiran et al. 2021).

1.9 Wheat Rust Interaction

Wheat and rusts interact on the basis of gene for gene hypothesis and strictly follow the rules of Mendelian inheritance. Generally, wheat resistance to rust diseases is controlled by dominant genes and virulence in wheat rust pathogens by recessive genes. It implies that avirulence is controlled by dominant genes. Wheat rust interaction manifests on the host surface in the form of definite phenotype. The expression of phenotypes (infection types) may be influenced by intensity of light and temperature range. Resistance (incompatible reaction) is the result of interaction between a resistant host and an avirulent pathogen. Several gene interactions do occur between wheat and rust pathogens (Bhardwaj 2013).

Under host–pathogen interaction, an effort was made to compare the expression patterns of defense-responsive genes at early stages of infection in susceptible and resistant lines which differ in *Lr24*-based resistance. Gene *Lr24* confers resistance to all pathotypes of *Puccinia triticina* in India. The expression levels of aquaporin, endochitinase, β-1,3-glucanase, phenylalanine ammonia-lyase, Type 1 non-specific lipid transfer protein precursor and caffeic acid O-methyltransferase were significantly higher in resistant response. In the incompatible response, comparatively high expression of aquaporin and phenylalanine ammonia-lyase was observed at the pre-historical stage, whereas expression of lipid transfer protein and endochitinase was high during the post-historical stage. This study could infer that differential expression of defense-responsive genes plays a pivotal role in compatibility or incompatibility of wheat to leaf rust. This understanding would facilitate in devising novel strategies to manage wheat leaf rust (Prasad et al. 2018b). The function of salicylic acid and sugar-mediated resistance mechanisms was also studied during the early stages of infection of wheat by leaf rust pathogen. The expression of the main salicylic acid (SA) regulators (TaEDS1, TaSGT1, TaPAD4, TaNDR1, TaRAR1, TaHSP90, TaPAL, TaEDS5 and TaNPR1) and sugar (TaHTP, TaSTP13A) pathways were examined between two wheat NILs with *Lr24* and without *Lr24*. The expression profiles of candidate genes using reverse transcription quantitative real-time polymerase chain reaction (PCR) at different time points post-inoculation revealed stage-specific transcriptional reprogramming of these genes between susceptible NIL and resistant ones. The genes acting upstream of SA in the SA pathway (TaEDS1, TaPAD4, TaRAR1, TaSGT1, TaNDR1, TaHSP90, TaEDS5) showed strong expressions after 48 h post-inoculation (hpi) in the susceptible NIL compared to unchanged or slightly changed expressions in the resistant response. Contrarily, the genes involved in SA downstream signalling (TaNPR1), SA biosynthesis (TaPAL) and sugar transportation (TaHTP, TaSTP13A) expressed highly at mid-phase of infection between 6 and 24 hpi in the resistance compared to the susceptible NIL. These patterns of gene expressions suggest that TaNPR1 and TaPAL play a positive regulatory role in the SA-mediated resistance pathway, whereas TaHTP (*Lr67*) plays an important role in the sugar-mediated resistance pathway induced by the leaf rust resistance gene, *Lr24* (Savadi et al. 2018).

During host–pathogen interaction, small ribonucleic acid (sRNAs) generated by host and pathogens could impart resistance or susceptibility due to RNA interference

(RNAi) mechanism. In one study, sRNA libraries were sequenced using Illumina sequencing technology. A total of ~1–1.28 million potential sRNAs and two micro-RNA-like small RNA (mil-RNAs) candidates were identified. Expression analysis of 20 selected sRNAs, targeting host genes pertaining to metabolic processes, transporter, reactive oxygen species (ROS)-related disease resistance, apoptotic inhibitor and transcription factors along with two pt-mil-RNAs by qRT-PCR, showed distinct patterns of expression of the sRNAs in urediniospore-specific libraries. A pioneering work has been done in identifying the novel sRNAs in *P. triticina* including two pt-mil-RNAs that may play a pivotal role in biotrophic growth and pathogenicity (Dubey et al. 2019).

1.10 Rust Resistance in Wheat

Resistant wheat cultivars have been a classic mechanism to manage rust diseases. A few historic cultivars, Hope and Thatcher for stem rust, Surpreza, Americano 25, Frontana and Fronteira for leaf rust, and Manella, Juliana, Wilhelmina, Capelle-Desprez, and Carstens VI for stripe rust, carried considerable level of resistance for many years. Several cultivars have remained resistant for 5 years or even more, that is, an average agronomic lifespan of a cultivar. Sometimes, resistance may last longer. However, some cultivars had become susceptible even before those were grown on a fraction of the cultivated acreage. In most cases, cultivars have become susceptible because of inadequate knowledge of the virulences existing in a pathogen population. In other cases, mutations or somatic recombination among existing virulences have occurred and rendered the host susceptible.

Rust resistance genes are categorized into two classes. The first class is R (for resistance) genes, which are race-specific in their action and effective at all growth stages of wheat. The second class is adult plant resistance (APR) genes. These genes usually express at the third leaf stage. APR can be non-race-specific (partial) or race-specific (both of hypersensitive and non-hypersensitive type). The levels of resistance conferred by single APR genes are only partial and allows substantial rust development (Kilpatrick 1975; Ellis et al. 2014). The landmark success of rust breeding programme had been against stem rust. This is because of an exhaustive research on this pathogen for a larger number of years. A number of cultivars carrying *Sr*26 have been released in Australia since 1971 and were grown on a large area without being affected by stem rust (Luig and Rajaram 1972). The adult plant resistance gene *Sr*2, derived from Hope, showed the absence of uredia on the internode tissues (Hare and McIntosh 1979). This has perhaps been the most commonly used *Sr* gene globally since the 1940s. Gene *Sr*31, imparted a high to moderate effective resistance to stem rust, was effective worldwide until 1998. Presently, it is common in many high-yielding wheat cultivars, including Burgus II, Lovrin 10, Aurora, Kavkaz, Riebesel, Siouxland, Alondra, Weique, Bartweizen, Nautica, Salzmuendu Clement, Pak 81, Faisalabad 85, Veery, Bobwhite and many thousands of germplasm lines or cultivated wheat lines.

Although 80 *Lr*, 59 *Sr* and 83 *Yr* genes have been designated worldwide (McIntosh Pers. comm.), however, virulence occurs for a majority of them. Therefore, the best control strategy would involve combinations of these race-specific and non-race-specific genes. Many spring wheat cultivars developed by CIMMYT have shown a slow rusting type of resistance (Rajaram et al. 1996). Gene *Lr*34 along with the other undesignated slow rusting genes is believed to impart a durable resistance in Frontana and other wheat cultivars (Singh and Rajaram 1992). Gene *Lr*46 in combination with an unknown slow rusting gene is onus for slow rusting resistance in cv. Pavon 76 (Singh et al. 1998). The usefulness or durability of resistance is not associated with the donor genera or species.

1.11 Evaluation of Germplasm for Rust Resistance

A foolproof screening system of germplasm assessment is necessary for identifying rust resistance sources. It is ensured that uniform rust epiphytotic is created by providing optimum conditions for infection of rusts. All the wheat germplasm developed under the umbrella of All India coordinated Wheat and Barley Improvement Project, and other materials are subjected to rigorous screening at seedling (all time), race-specific APR at IIWBR, Regional Station, Flowerdale, Shimla, H.P., and also at many coordinated centres for APR to different rusts. The screening involves challenging each wheat line against the most virulent and predominant pathotypes with different avirulence/virulence structures. Studies involve screening of wheat material at seedling stage against 70 different pathotypes of three rust pathogens under controlled conditions of temperature and light. At the same time, race-specific adult plant evaluation is undertaken at Shimla and other centres also. Similarly, non-race-specific screening of Advance Wheat Trial material is also carried out at many centres to calculate area under disease progress curve. At the same time, genetics of rust resistance is also investigated. Based on the gene matching technique, rust resistance genes are characterized in wheat material. All these aspects enable the selection of lines with diverse rust resistance. This information is used for the identification of new varieties and varietal deployment.

1.12 Gene Mining and Gene Discovery for Rust Resistance in Wheat

Efforts are on world over to search for novel and unexplored rust resistance genes available in old wheat varieties, present-day wheat material, local germplasm, alien sources and exotic accessions. Such genes have been identified to confer leaf or and stripe rust resistance in CIMMYT, Mexico, Australia and many other countries. In fact, the gene inventory was enriched more in the last 20 years than ever before. Recently, in India, a major rust resistance gene *Lr80* was identified from local wheat landrace, Hango-2 and mapped on 2DS chromosome (Fig. 1.2).

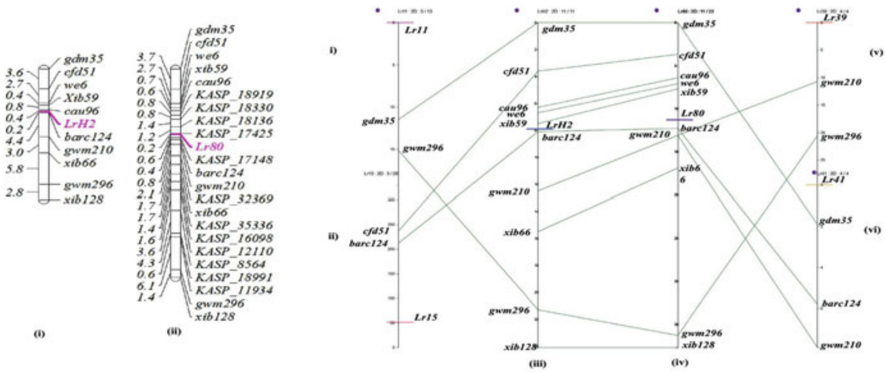

Fig. 1.2 Genetic linkage maps of Agra Local/Hango-2 population (1) *LrH2* present study SSR map, (2) *Lr80* SSR and SNP map

This gene confers resistance to all the predominant and virulent pathotypes of *P. triticina* in India (Kumar et al. 2021). This landrace was collected from Hango, District Kinnaur, Himachal Pradesh, India. Hango-2 exhibits a low infection type (IT) to all Indian *P. triticina* pathotypes, except the pathotype 5R9–7 which shows IT 3+. Pathotype 5R9–7(16–1) does not infect bread wheat cultivars and, however, is virulent on tetraploid wheat Khapli. Pathotype 5R9–7 is not prevalent in nature for the last 15 years. Genetic analysis based on Agra Local/Hango-2-derived F_3 families indicated monogenic control of leaf rust resistance, and the underlying locus was temporarily named *LrH2*. Bulked segregant analysis using 303 simple sequence repeat (SSR) markers located *LrH2* in the short arm of chromosome 2D and was formally designated as *Lr80*. Gene *Lr80* is flanked by markers *cau96* (distally) and *barc124* (proximally). The 90 K Infinium SNP array was used to identify SNP markers linked with *Lr80*. Markers *KASP_17425* and *KASP_17148* showed association with *Lr80* (Kumar et al. 2021). This gene is being used to develop rust-resistant genetic stocks and wheat varieties. It would help in creating diversity of rust resistance and management of leaf rust in India.

1.13 Anticipatory Wheat Breeding and Pyramiding of Resistance

With the discovery of Biffen (1905) that resistance to stripe rust in wheat is inherited in Mendelian way, it paved a way for rust resistance breeding. Subsequently, new wheat varieties were bred with an objective to manage rusts. Systematic breeding for rust resistance in wheat began in the early 1950s in India. Much has been achieved through the years in managing the rusts by planting resistant cultivars conferring diverse resistance. The genetic diversity among the cultivars has proved an effective strategy in managing the rust diseases, reducing the quantum and frequency of rust epidemics and understanding the rust epidemiology. The resistance gene *Lr26* together with *Lr13, Lr23* and *Lr34* and *Lr24/Sr24* segment from *Agropyron* have played a pivotal role in imparting field resistance and enhancing wheat production.

Pre-emptive or anticipatory breeding is a breeding for resistance to future pathotypes, in terms of development of cultivars resistant to future threats. It requires a relevant knowledge of the pathogenicity of pathotypes and host resistance genes deployed over wheat-growing areas. Resistance breeding strategies are usually supported with the maintenance of genetic diversity to provide buffering against extreme crop losses in case of epidemics. It basically refers to devising strategies for tackling the future pathotypes. It is assumed that new pathotypes will evolve from the prevalent pathotypes through mutation with respect to single-host resistance genes. It is also anticipated that future pathotypes would have the ability to overcome one or more of the resistance genes, which are deployed in recently grown wheat cultivars. Under Indian conditions, mutation occurring in the rust pathogens is the prime cause of variability. Three factors, namely, genetic diversity, durability and effectiveness are considered the most important in pre-emptive breeding. Host genetic diversity is encouraged to provide a bulwark in case of a rust outbreak. Information on genetic diversity and recommended cultivars is made available to extension personnel and farmers to assist in decision-making processes and to issue an advisory.

Another important aspect which cannot be left behind in case of pre-emptive resistance breeding is the frequent pathotypic surveys in farmers' fields, hotspots and disease trap nurseries. A vigilant and relevant pathogenicity survey monitors variability in pathogen populations. If resistances are based on genes effective only at the adult plant stages, the adult plant resistance (APR) tests should be conducted every season at hot spots for the disease. Many surveys monitor an arbitrary array of seedling resistance factors, and the information usually is of limited use to wheat breeders. Our national-level surveys jointly done by ICAR institutes and State Agricultural Universities have two major objectives. First, pathogenicity genes are used as markers in monitoring the origins, movement and epidemiology of rust pathogen populations and second, they monitor the disease responses conferred by the available resistance genes actually deployed in the region. With relevant information on pathogenicity from surveys and genetic information from host studies, it is feasible to opt for a limited number of pathotypes for screening the selection nurseries. Genetic studies are most suitably conducted with single pathotype in order to avoid the complexities that occur when resistance to a pathotype mixture is due to gene combinations (McIntosh 1992). Another point to be considered for pre-emptive breeding efforts calls for detailed knowledge about pathogenic variation and factors responsible for it. Migration has been reported as a major factor for variability in pathogen population structure. There is a strong proof that anthropogenic activities also contribute to the dispersal of wheat yellow rust. For instance, European travellers first introduced yellow rust pathogen into Australia in 1979 (Wellings 2007). The introduction of inoculum followed by successful establishment of introduced pathotypes from outside the area has become a frequent problem. Earlier, only wind-borne entry was suspected (Nagarajan and Joshi 1985; Watson and de Sousa 1982). Once introduced, further introductions of identical or similar pathotypes cannot be recognized. Pathogens that become established in one region having favourable conditions for its growth rapidly appear and try to establish in other regions adjusting to the changing requirements for its survival. Evolutionary pathways can be successfully constructed to show the occurrence of mutational changes over time with the help of bio-informatics.

The role of mutation and recombination in the evolution of pathogens to create variability cannot be ignored. *Puccinia striiformis* populations in some parts of the globe are highly clonal, especially in India, Australia and Europe. Since *Berberis* species do not play any role in completion of sexual life cycle and perpetuation of the stripe rust pathogen in India (Mehta 1940), probably, mutation and adaptation to popular regional cultivars are the primary mechanisms of evolution and selection of new pathotypes (Gangwar et al. 2016). Pathotype 46S119 evolved independently from the known pathotype 46S103 by gaining virulence to *Yr9* (Prashar et al. 2007). It appears that a genetic change occurred recently in pathotype 46S119 resulting in additional virulence to differentials Suwon92xOmar and Riebesel 47/51, and pathotypes 110S119 and 238S119 got evolved. Similarly, pathotype 78S84 gained additional virulence to cv. Strubes Dickkopf and gave rise to pathotype 110S84 (Gangwar et al. 2019). Thus, selection of pathotypes facilitated by the host genotypes with relevant resistance factors is a major driving force through which mutant newly or introduced pathotypes increase in frequency.

1.14 Rust Management Strategies

The genetic resistance is the most economic, ecologically safe and effective way to manage wheat rusts. Use of effective bio-pesticides or biological agents, chemicals particularly of triazole group, interventions in cultural practices, continual monitoring of rust diseases and deployment of rust-resistant varieties are the popular strategies for wheat rusts' management. A novel strain of *Alternaria alternata* was able to penetrate and colonize the urediniospores of yellow rust pathogen (Zheng et al. 2017). This hyperparasite seems to be less promising as biological control agent, because of rapid production of rust spores and their aerial dispersion. However, *Bacillus subtilis* strain E1R-j was reported effective in wheat stripe rust management (Li et al. 2013). Other biological control agents such as *Trichoderma* spp., *Bacillus* spp., *Streptomyces* spp. and arbuscular mycorrhizal fungi can also be used for managing wheat rusts (El-Sharkawy et al. 2018; Huang and Pang 2017; El-Sharkawy et al. 2015). Application of a fungicide is generally recommended when the cultivar is susceptible, and the disease has appeared at the early stage. For maximizing the cost–benefit ratio, fungicides must be applied between flag leaf formation and complete head emergence. Post-flowering application of fungicide would not economically feasible because a considerable damage to the flag leaf will have occurred by that time. Protecting the flag leaf is of utmost importance. Fungicides such as propiconazole 25% EC (Tilt), difenoconazole 25% EC (Score), azoxystrobin 25% SC (Amistar) and tebuconazole 25% EC (Folicur) could be used effectively (@ 0.1%) to manage wheat rust diseases. Fungicides tebuconazole

(Folicur 250 EC), tebuconazole + tridimenol (Silvacur 375 EC), tebuconazole (Orius 25 EW) and AmistarXtra 280 SC, individually or in combination, were highly effective in avoiding black rust epidemics in Kenya (Wanyera et al. 2009). Despite all the benefits associated with the application of fungicides, there is always risk of development of fungicide resistance in rust fungi, which results in reduction or loss of fungicide sensitivity in these pathogens (Arduim et al. 2012).

There is a need to devise more harmonized ways of managing the threat of plant diseases such as wheat rusts by integrating different plant breeding, chemistry, biotechnology and bioinformatic tools for a practical and sustainable crop protection (Lucas et al. 2015). Alternative novel approaches using biotechnological tools such as genomic selection, cis-genesis, intra-genesis, sequence-specific nuclease technology, oligonucleotide-directed mutagenesis, gene cassettes, RNA-dependent DNA methylation, pathogen effectors guided breeding and reverse breeding are being developed and employed for breeding broad-spectrum and durable disease resistance in crops (Prasad et al. 2019; Savadi et al. 2017).

1.15 Conclusion

Diversity is the keyword for wheat rust management. Much has been achieved in managing the wheat rusts through deploying resistant wheat varieties having diverse resistance in India. A blend of all time (seedling), slow rusting, adult plant rust resistance genes of both race-specific and non-race-specific types are considered for the deployment of wheat varieties. It would not only avoid the severe losses due to wheat rusts but also increase the self-life of wheat cultivars and discourage evolution in rust pathogens. Skillful deployment of wheat cultivars based on the knowledge of pathotypes distribution has led to the successful management of wheat rusts in India. In recent years, wheat has shown relatively higher production stability as compared to other cereal crops through strategic gene deployment (Tomar et al. 2014). A combination of cultural management practices, deployment of rust-resistant genotypes and fungicide application (in case of emergent situation) would be the most effective module for managing the wheat rust diseases.

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2 Forecasting of Wheat Diseases: Insights, Methods and Challenges

Jaspal Kaur, Ritu Bala, and Parminder Singh

2.1 Introduction

On the global level the plant diseases are known to cause huge losses in terms of quality and quantity (Agrios 2005; Strange and Scott 2005; Chakraborty and Newton 2011; Savary et al. 2012). Plant pathologists are making their best efforts to reduce these losses by using the different strategies of plant disease management singly or in combination. But each one has its own advantages and disadvantages in different host-pathogen interaction systems. E.g. in some crops the resistance sources are not available, in some crops good number of resistance sources is available but due to continuous evolution of the pathogen(s) that does not last long. In some diseases especially seed and soil borne diseases, the seed or soil treatment with biocontrol agents or biofugicides are effective (Akhmedovich et al. 2020) but in some biological control is restricted to laboratory. Fungicides are giving good management of plant diseases but in case of soil borne diseases it is not possible to use large amount of fungicides to treat the soil due to problem of persistence and harmful effects on non-target soil borne organisms. In some diseases due to polycyclic nature of the pathogen or fast multiplication, the chances of fungicide resistance development will increase (Lucas et al. 2015). Moreover due to increased public awareness and environmental issues etc. the application of

If "technology transfer tool" can be defined as a way to get information into the hands of as many people as possible, weather-based disease forecasting models are the perfect example of how this works in practice.: Julienne Isaacs.

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fungicides is restricted although their application has given a boom to the yield in almost all the crops. Above all the irrational or non-optimal use of the fungicides/ pesticides leads to an economic loss to farmers, as well as crop and land quality. Most recently a draft on the banning of 27 pesticides has been released by the Indian Government due to their ill effects on humans, animals and environment etc. (The Economic Times 2020). So the efforts of the plant pathologists are targeted towards the integrated disease management to minimize the use of fungicides. Wherever other management practices don't work properly, and use of fungicides is the only option; in that case judicious use of fungicides i.e. application at proper time with exact dose, spray volume and right kind of spray pumps and nozzle is desirous. Timely application of fungicides based on the epidemiology of the particular disease results in effective management of that particular disease otherwise the application goes waste. Both in case of monocyclic (Head Blight, Septoria Blight) and polycyclic diseases (Rusts) several epidemiological models have been developed in different crops for timely plant protection measures. In simple words the plant disease forecasting is the prediction of the occurrence or changes in severity levels of plant diseases in relation to weather, crop, or pathogen. The process of forecasting involves all the activities like ascertaining and notifying the growers of community that conditions are sufficientlyfavorable for certain diseases, the timely application of control measures will result in economic gain. Different reviews on the various aspects of disease epidemiology and modeling of plant diseases (Zadoks and Rabbinget 1985; Teng 1985; Madden 2006; Savary et al. 2018) has been published which clearly described the types of modeling approaches starting from intial equations to linked differential equation models (Madden 1980; Madden 2006; Madden et al. 2007).

The principle behind plant disease forecasting systems is to determine the risk that a disease will pose, or the the intensity of the disease will increase (Campbell and Madden 1990). Norton et al. (1993) stated the possible objectives for modelling in fungal epidemiology include (1) Predicting the timing of an event i.e. when disease infection is likely to occur; (2) Predicting the scale of an event; such as the severity of disease infection or crop loss; (3) Estimating the frequency or the probability of an event, such as monocyclic (Karnal Bunt) or polycyclic epidemics (Rusts); (4) Assessing and comparing the performance of different management strategies. So, basically the epidemiologists are detectives which watch the each and every activity of the pathogen and each step of the disease development critically. Wade Hamptom Frost, the dean of American epidemiologists in 1927 stated that "The nature and spread of a disease may often be established quite firmly by circumstantial evidence well in advance of experimental confirmation" (Stolley and Lasky 1995).

The predictive systems are of two different types i.e. the one that predict disease and the other that predicts infection (Bourke 1955). All the prediction models can be further categorized on the basis of their development i.e. empirical or fundamental. The empirical predictive systems are developed by studying and comparing historical records of disease occurrence and concurrent weather conditions in the same or approximate locality. Such systems usually result in the formulation of "rules" or specific meteorological conditions that must be fulfilled before disease development can take place. The fundamental predictive systems are developed based on the data obtained experimentally in the laboratory or field regarding the relationships of biological and environmental conditions governing host-pathogen interactions. The utility of the predictive systems can be assessed by three different overlapping criterions i.e. conceptual utility, developmental utility, and the output utility (usefulness of the model to the farmer).

The success of forecasting system depends upon its reliability i.e. it should be based on the sound biological and environmental data, simple, developed for the disease of economic importance with risk of spreading on the larger area if not controlled at initial stages. The necessary information about the components of the models should be available, should be of multipurpose applicability, and above all it should be cost effective. Most of the disease forecasting systems available till date are based on reducing the initial inoculum (soil borne diseases/monocyclic diseases) and in polycyclic diseases with large amount of initial inoculum and lesser number of secondary cycles) or controlling the apparent infection rate(in polycyclic diseases with low initial inoculums and more number of secondary cycles/inoculums) and hence provide information on how a grower's management decisions can help to avoid initial inoculum or to slow down the rate of an epidemic. These two concepts are of utmost importance as they are able to differentiate the risk for a monocyclic disease (having only one cycle of infection) versus polycyclic disease, where there are multiple infection cycles, and a forecasting system can be used to time appropriate management tactics. (Madden et al. 2007). Some forecasting models focus both on avoiding primary inoculum and also on reducing the rate of the epidemic development during the season especially in case of diseases in which more initial inoculum is present and also they multiply rapidly with more number of secondary generations. (Agrios 2005; Campbell and Madden 1990). Better understanding of the host, and environment and its influence on the pathogen and disease development, available detection technology for that particular disease/pathogen and in depth knowledge about the disease and pathogen dynamics helps in the development of a successful forecasting model with sufficient accuracy. After the development of the forecasting model the proper validation is the key criterion for its wider adoption. There is increased interest among plant disease modelers and researchers to improve cost benefit ratio through validation based on quantifying the cost of a model making false predictions (positive and/or negative). An economic validation of a plant disease forecasting system requires the examination of two false predictions (a) false positive predictions, in which a forecast was made for a disease when in fact no disease was found in a location, and (b) false negative predictions, in which a forecast was made for a disease not to occur when in fact the disease was found. These two have different economic effects for producers (Madden 2006). Flexibility of the model, its accuracy, statistical representation of interaction and contact assumptions, defining the critical threshold of transmissibility, methods followed to model disease dynamics incase of pathogens which can travel long distances with the help of air and identification of natural scale to trackmovement and interaction with host are the key challenges for advancing the models (Newbery et al. 2016).

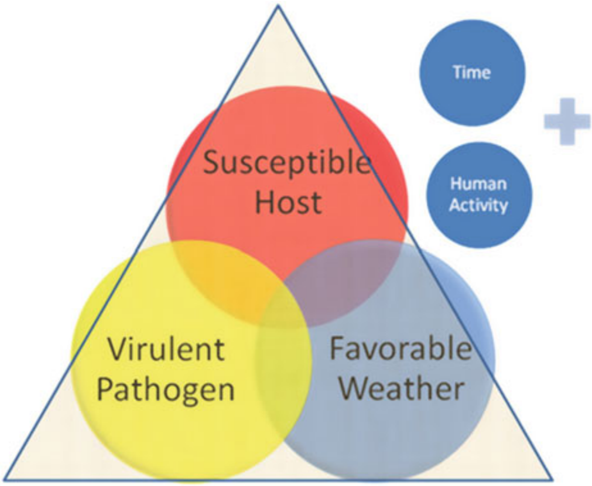

Fig. 2.1 Components for the development of plant disease epidemic

Since the focus of the chapter is on forecasting of wheat diseases and crop is known to be affected by different diseases among them the important ones are rusts (stripe, stem and leaf) foliar blights, smuts and bunts, Fusarium head blight and Blast. These diseases are known to cause huge losses annually at global level (Reis et al. 2000; Hovmøller 2001; Kohli et al. 2011; Savary et al. 2012; Newbery et al. 2016; Jindal et al. 2012). In wheat diseases especially in case of rusts the main goal of the wheat breeding always remains to increase host resistance by deploying variety of resistance genes which decrease the chances of resistance breakdown by the pathogens (Ojiambo et al. 2017). But development of new races with more virulence, aggressiveness and better adaptability to high/low temperature gives a new direction to the crop breeding programme. In the absence of the effective resistance cultivars the role of fungicides becomes prominent for the management of the quick spreadingdiseases like rusts. In such cases decisive system is needed for the timely application of fungicides to reduce economic cost, environmental impacts and yield losses. Under these situations the importance of epidemiologists increases to have good and effective disease forecasting models applicable for single disease or multiple diseases in same crop or different crops. The discipline of epidemiology gained its status after the publication of book, Plant Diseases: Epidemiology and Control in 1963 by Vander Plank. In this period of around 57 years the concept of disease pyramid (Disease triangle+Time + human activity) has evolved from disease triangle (Host, pathogen and Environment) (Fig. 2.1) and the discipline has gained much application in terms of technological advancements for the development of disease prediction models. The computer based systems has increased the speed and accuracy of the forecasting models.

This book chapter will focus on the various forecasting models designed by various researchers for different wheat diseases (Fig. 2.2), insights into those models and challenges before the epidemiologists to develop more accurate, reliable and cost effective forecasting models in wheat crop under different agro-climatic zones

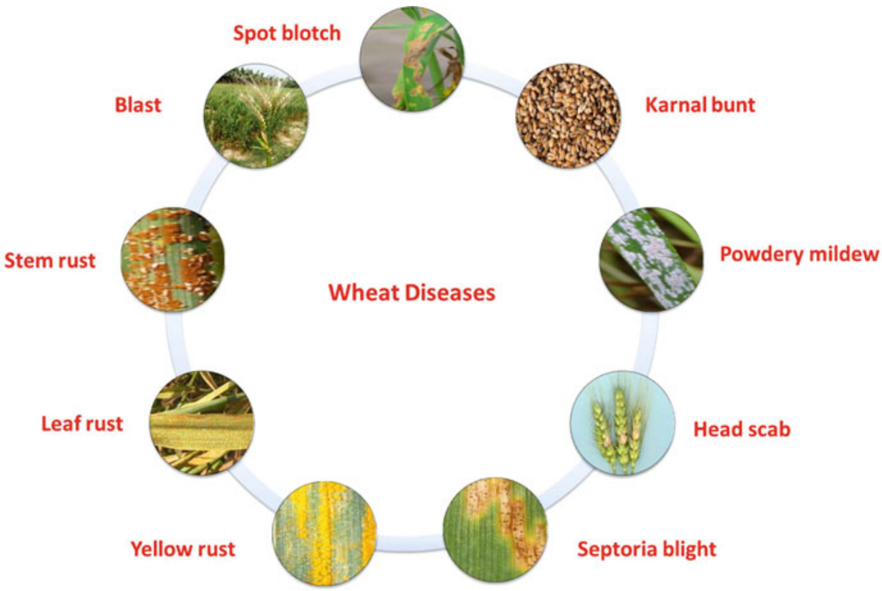

Fig. 2.2 Main wheat diseases for which forecasting models have been discussed

for a single disease or for prediction of multiple wheat diseases. Like all other crops three different types of disease prediction models i.e. Empirical (based on field observations); Simulation models (based on theoretical relationships) and general circulation models (based on fixed changes in temperature or precipitation to predict disease expansion range) are used for wheat disease forecasting.

2.2 Rusts

Rusts are the known to cause the significant economic damage in cereals worldwide. All the stages of rust development staring from landing of the uredospores, followed by their germination, penetration into host, reproduction, colonization, symptom development, disease severity and secondary spread of the pathogen all are affected by the weather parameters such as temperature, relative humidity, wind speed and direction etc. Rust diseases develop and spread rapidly under favourable conditions. Three different types of rusts; stem rust/black rust (*Puccinia gramins tritici*) leaf/ brown rust (*Puccinia recondita*), yellow/stripe rust (*Puccinia striiformis tritici*) affect wheat crop from seedling stage to maturity (Bhardwaj et al. 2016; Kaur et al. 2018). Each *Puccinia* species has particular environmental requirements that include presence of free film of water on the leaf surface (due to intermittent rains or heavy dews) and temperatures optimum for the germination and growth of thefungus (Marsalis and Goldber 2017). *Puccinia* spp. causing rust diseases in wheat are polymorphic in nature and produce five different types of spores namely, picniospores/spermatia, aeciospores, uredospores, teliospores and basidiospores. Vast number of spores is produced by the rust fungi which travel long distances with the help of wind (Visser et al. 2019) and in the presence of susceptible host and favorable weather conditions can cause huge losses or can lead to epidemic like situation in very short period of time (Leonard 2001). For the rust diseases the top priority of the wheat breeder is always to have a cultivar(s) with good yield and rust resistance to achieve sustainable crop yield. Owing to fast multiplication of the pathogen and continuous evolution the new races of the fungus with enhanced virulence, aggressiveness and better adaptation develop which most of the times overcome the resistance. Moreover the effectiveness or performance of some of the resistance genes is also affected by the environmental conditions but the basis for which is poorly understood (Bryant et al. 2014). Many epidemics have been reported globally due to the wheat rusts which resulted in big yield losses. Best approach in the absence of resistance is the timely application of fungicides. Incase of rusts the fungicide application must generally occur during the early stages of epidemics, and at sufficient rates. Over-application is costly and creates added selection pressure for more fungicidal tolerant strains; while under-application may also be cost-prohibitive in regions where expected yield is lower (Chen 2007). In such cases the disease prediction models help to take the decision that when to apply the fungicide and where to apply i.e. targeted application of fungicides. In case of wheat rusts most of the disease prediction models are based on environmental conditions as numerous environmental factors are there and their affect on disease development vary with growth stages, season to season and region to region. So the identification of the critical factors involved in the initiation of disease and development at different growth stages of the crop in different regions help to predict the disease accurately by working out the correlation coefficients between each environmental variable and the observed "target variable" i.e. disease severity level (Gouache et al. 2015). These results serve to improve the understanding of the studied pathosystem and provide useful knowledge for managing the disease (Gouache et al. 2015). For wheat rusts till date many disease prediction models have been developed in different countries by using the different parameters and different approaches which included simple regression analysis (Eversmeyer et al. 1973), discrimination analysis (Chen et al. 2006), principal component analysis (Naseri and Sharifi 2019), grey model forecast method (Pu 1998), neural networks (Wang and Ma 2012), support vector machine (Wang and Ma 2011), Markov forecast method (Qiang 1999) etc.

2.2.1 Stripe Rust of Wheat

A number of studies have been conducted throughout the world for predicting stripe rust of wheat early in the season (Zeng 1962; Coakley et al. 1982; Murray et al. 1994; Hu et al. 2000; Fan et al. 2008; Wang et al. 2016; Mulatu et al. 2020). Each study has its own data requirements and complexities which are summarized in the Table 2.1 and only a few are discussed below. The prediction of stripe rust of wheat

Table 2.1 Disease prediction models developed globally for stripe rust of wheat caused by *Puccinia striiformis tritici*

Year	Parameters taken into considerations/ Methods used	Area/Country	References
1962	Number of rainy days, precipitation and mean temperature of 10 days from 11March to 20 April.	China	Zeng (1962)
1981	Temperature(January, April and June), precipitation in June and positive as well as negative degree days	Pullman	Coakley and Line (1981)
1982	Standardized degree days positive and negative (PDD& NDD)	US Pacific northwest	Coakley et al. (1982)
1983, 1984	PDD, NDD, Julian day of spring	US Pacific northwest	Coakley et al. (1983, 1984)
1983	Disease development data to calculate yield loss due to rust attack at soft dough stage	Victoria	Brown and Holmes (1983)
1987	Temperature and wet period	Australia	Dennis (1987)
1988	PDD, NDD, Julian day of spring, mean max.Temperature, total precipitation, precipitation frequency, number of days with temperature more than 25 °C and number of days with temperature less than 0 °C	US Pacific northwest	Coakley et al. (1988)
1994	Affected area at early milk stage, time and daily maximum temperature(seven days before to one days after early milk stage)	Australia	Murray et al. (1994)
1995	Temperature, dew duration & wetness	France	De Vallavieille-Pope et al. (1995)
2000	Amount of pathogen inoculum in autumn of the last year, amount of pathogen inoculum in spring, average temperature & precipitation in April and area under susceptible variety	Hanzhong in Shaanxi Province/China	Hu et al. (2000)
2003	Disease on lower canopy of plants	UK	Young et al. (2003)
2007	Temperature, dew formation, cultivar resistance rating, frost, seed treatments and foliar fungicide applications	England	Gladders et al. (2007)
2007	Diseased fields (%) in autumn in preceding year, area under susceptible variety, average tem. In January and maximum temperature in march	Longman mountainous area in southern Gansu/China	Xiao et al. (2007)
2007	Precipitation in middle 10 days of April and last 10 days of may, precipitation in middle and last 10 days of may & average relative humidity in may	Shanxi Province	Fan et al. (2007)

(continued)

Table 2.1 (continued)

Year	Parameters taken into considerations/ Methods used	Area/Country	References
2008	Average temperature in march, precipitation in march–may and area under susceptible varieties.	Gangu, Gansu/ China	Fan et al. (2008)
2008	Temperature from February to June and rainy days	UK	Beest et al. (2008)
2008	Weather correlations with disease severity and predictions were made using BP neural network with its network structure simplified through PCA and with its initial weights and threshold optimized by GA.	China	Zeng and Luo (2008)
2009	Incidence is correlated to temperature in Feb. & march and severity is correlated to precipitation in Jan & Feb and temperature in June	S. Sweden	Wiik and Ewaldz (2009)
	Disease prevalence in spring, amount of over-summering pathogen, total precipitation in September-october	Pingliang region in eastern Gansu	
2010	Precipitation in last 10 days of July in the preceding year, sunlight in the first 10 days of November and march in the preceding year,, average temperature in the middle 10 days of April and precipitation in the last 10 days period of April.	Jincheng region in Shanxi Province	Cheng et al. (2010)
2013	Web based geographical information system (WeBGIS)	China	Kuang et al. (2013)
1994	Assessment yield losses due to stripe rust at different growth stages from end of heading to late milk in relation to temperature	Australia	Murray et al. (1994)
2006	Discrimination analysis for the forecast of wheat stripe rust based on the occurrence data of this disease and the climate data	China	Chen (2007)
2011	Neural networks	China	Wang and Ma (2011)
2014	Hyperspectral reflectance data	India	Krishnaa et al. (2014)
2016	Hyper spectral data acquired using a black-paper-based measuring method	China	Wang et al. (2016)
2017	Stepwise regression analysis showed existing of low temperature (10–12 °C), high relative humidity (90%) along with intermittent rainfall was conducive for disease onset. Thermic variables (atmospheric, canopy and soil temperature) along with age of crop in the selected varieties showed significant positive correlation with disease severity	India	Gupta et al. (2017)

(continued)

Table 2.1 (continued)

Year	Parameters taken into considerations/ Methods used	Area/Country	References
2019	Air temperature, icy and rainy days, relative humidity	Iran	Naseri and Sharifi (2019)
2020	Rainfall, relative humidity, and air temperature conditions	Morocco	El Jarroudi et al. (2020)
2020	Rainfall, relative humidity and temperature were by machine learning tools	Ethopia	Mulatu et al. (2020)
2020	Non linear prediction model (classification regression tree (CART) using night temperature, dew point temperature, relative humidity data	Mexico	Rodriguez Moreno et al. (2020)

based on weather variables is as old as the science of epidemiology is (Zeng 1962). During the year 1978 a disease prediction model EPIPRE (EPidemics PREdiction and PREvention) for stripe rust of wheat was launched in Netherland and Belgium promoted after the heavy epidemics of yellow rust in 1975 and 1977 in Netherland and is a kind of simulation model which works on field-by-field basis(Rabbinge and Rijsdijk 1983). EPIPRE is a system of supervised control of diseases and pests in winter wheat. In this system the participating farmers do their own monitoring of diseases and pests and send that information related to field, crop stage and disease/ pest to the data bank which then fed into the computer based model. Field data updated daily and by simple simulation models expected damage/loss were calculated and used in making decision i.e. to spray or not to spray. Initially this model was operational in Netherland and Belgium for stripe rust only later on it was used for making decisions related to leaf rust, powdery mildew, septoria blight, glume blotch and aphid during the successive years (Smeets et al. 1994). Shtienberg et al. (1990) developed a threshold level forecasting model and finally on the basis of the pathological parameters and weather forecasts developed a Wheat disease control advisory (WDCA), a computerized decision support system for septoria blotch, leaf rust, and yellow rust, under the semi-arid conditions of Israel. In the decision making process, the system take into consideration the economic, agronomic, phytopathological and both recorded and forecasted weather. It provides a recommendation for fungicidal action to reduce the diseases efficiently in time after analyzing the effects of thevarious factors on the benefits of disease control. The advisory system was tested over 4 years in 81 field experiments by the developers and commercial growers. In managed fields as per advisories of WDCA, a significant increase of 0.78 t/ha in yield, or US $ 92.70 per ha in net profit, was obtained relative to the common management policy. El Jarroudi et al. (2017a) in Luxembourg developed a threshold-based weather model for predicting stripe rust. In this model first, by using the Monte Carlo simulation method based on the Dennis model, the range of favorable weather conditions were characterized. Then, the optimum combined favorable weather variables (air temperature, relative humidity, and rainfall) during the most critical period of infection (May–June) were identified and then were used to develop the model. Uninterrupted hours with such favorable weather conditions over 10-day period during the months of May–June were also considered while building the model. A combination of relative humidity >92% and 4 °C < temperature < 16 °C for a minimum of 4 continuous hours, associated with rainfall ≤0.1 mm (with the dekad having these conditions for 5–20% of the time), were optimum to the development of a wheat stripe rust epidemic. The model accurately predicted infection events: probabilities of detection were ≥ 0.90 and false alarm ratios were ≤ 0.38 on average, and critical success indexes ranged from 0.63 to 1. Naseri and Sharifi (2019) used Principal component analysis (PCA) to identify climatic variables associated with occurrence and intensity of stripe rust epiphytotics in Iran. They found that disease epidemic intensity was linked to the number of rainy days, the number of days with minimum temperatures within the range of 7–8 °C and relative humidity (RH) above 60%, and the number of periods involving consecutive days with minimum temperature within the range of 6–9 °C and RH% > 60% during a 240-day period, from September 23 to May 21. Sadar et al. (2019) firstly developed wheat rust (stripe and stem rust) early warning system (EWS) in which near real-time field survey observations and advanced numerical weather prediction (NWP) meteorological forecast data, Lagrangian spore dispersion forecasts along with detailed environmental suitability model forecasts, and wide-ranging communication methods were used collectively to predict near real-time risks of disease occurrence in Ethopia.

El Jaroudi et al. (2020) made efforts to couple the use of artificial intelligence algorithms with weather based models for predicting in season development of stripe rust of wheat. They used mechine learning techniques such as random forest, naïve bayes alogrithims and multivariate adaptive regression alpines for stripe rust prediction in Morocco. A combined effect of relative humidity >90%, rainfall ≤0.1 mm, and temperature ranging from 8 to 16 °C for a minimum of 4 continuous hours (with the week having these conditions for 5–10% of the time) during March–May were optimum to the development of WSR epidemics. Dong et al. (2020) developed an automatic system for Crop Pest and Disease Dynamic Monitoring and Early Forecasting of stripe rust of wheat and locust based on web GIS platform. Wheat rust index (WRI) was constructed based on plant senescence reflectance index (PSRI) and red-edge vegetation stress index (RVSI) to monitor wheat yellow rust, for which WRI could consider wheat growth, chlorophyll content and their variation characteristics. Then, integrated with disease habitat information including land surface temperature (LST, MODIS product), rainfall and wind (meteorological data), also historical data, Disease Index (DI) was constructed for wheat yellow rust habitat monitoring based on previous work. Rodríguez-Moreno (2020) in Mexico explored the use of the classification and regression tree (CART), a type of nonlinear prediction model, to know the key weather–disease links in case of stripe and leaf rust of wheat.

Comparisons of different types of models for their efficacy, accuracy were done by various workers in. Nei et al. (2014) did the comparison of methods for forecasting yellow rust in winter wheat at regional scale. They compared the

Bayesian network (BNT), BP neural network (BP), support vector machine (SVM), and fisher liner discriminant analysis (FLDA) used to develop YR forecasting models and found that three methods of BNT, BP neural networks and SVM are of great potential in development of disease forecasting model at a regional scale. Gouache et al. (2015) used Window Pane analysis for identifying synthetic weather variables over overlapping time frames for eachgrowing season. The correlation coefficients between each variable and the observed "target variable"i.e. the disease level at the end of a season were calculated and critical periods were identified during which the variation in specific environmental variable(s) lead to variations in level of disease expression. Newlands (2018) evaluated the two models; CLR model, which is a simple, site-specific model, and hhh4 model; a complex and spatially-explicit transmission model. The ability of these models to reproduce an observed infection pattern is tested using two climate datasets with different spatial resolution-a reanalysis dataset (~55 km) and weather station network township-aggregated data (~10 km). Thehhh model using weather station network data had the highest forecast accuracy and reliability under heterogeneous modeling assumptions.

Many prediction models have been developed for forecasting of stripe rust of wheat. However, each model has its own advantages and shortcomings and certain application conditions. According to the region or actual conditions suitable model should be selected for application. Prediction model system for yellow/stripe rust of wheat could be built to collect the prediction models into one computer system through programming the models. It could make easier to choose suitable model. Integrated prediction model could be established using different models and methods according to the needs in the future.

2.2.2 Leaf Rust

For the forecasting of leaf rust two different approaches have been used by many researchers throughout the world; firstly considering the influence of weather parameters on the disease (regression equations/disease indicies/flow charts etc) and secondly forecasting disease severity on the basis of epidemic dynamics i.e. from growth rate of the disease. Like stripe rust, again the temperature, relative humidity and rain fall are the key weatherparameters, which are known to influence the disease development and forms the basis for predicting WLR by various disease modelers (Table 2.2) starting from 1969 by Eversmeyer and Burleigh to 2020 by Rodrigues Moreno, a few has been discussed below.

In India during 1980, Nagarajan et al. gave a biclimatic model for prediction of leaf rust in northwestern India. They reported that the following criteria need to be satisfied if an epidemic is to occur. 1. During the period of January 15 to January 20, a wheat disease survey in UP and North Bihar should detect infections in at least five or six sites, separated by a minimum of 25 ± 5 km. 2. The number of rainy days from January to mid April over northwestern India should be at least double the normal of 12 days. 3. Over northwestern India the weekly mean maximum temperature during March to mid April should be ±1 °C of normal (26 °C).

Table 2.2 Disease prediction models developed globally for Leaf rust of wheat caused by *Puccinia triticina*

Year	Parameters taken into considerations	Area/ Country	Reference(s)
1969	Weekly uredospore number,commulative uredospore numbers, temperature, hours of free moisture as dew or rain/day and precipitation	USA	Eversmeyer and Burleigh (1969)
1972	Developed stepwise linear equation using number of spores trapped, temperature, wheat growth stage, fungal growth function, infection function, hours of free moisture and precipitation	USA	Burleigh et al. (1972)
1981	Linear equation model for predicting rust severity	India	Srivastava (1981)
1983	EPIPRE (EPIdemic PREdiction and PREvention)	Netherland	Rabbinge and Rijsdijk (1983)
1983	Higher temperature results in shorter latent and infectious perid	USA	Tomerlin et al. (1983)
1989	AUDPC, incubation period, Commulative degree days,hours of leaf wetness per day	USA	Suba Rao et al. (1989)
1990	Date of inoculation, weather variables, host susceptibility	USA	Rao et al. (1990)
1997	Meteorological conditions and uredospore cycles (RUSTDEP)	Italy	Rossi et al. (1997a)
1997	Weekly and monthly air temperature and rainfall.	Mississippi	Khan and Trevathan (1997)
1997	Step wise regression using weekly maximum and minimum temperatures, rainfall, relative humidity, wind speed and 24 hr. wind movement leaf rust severity.	Pakistan	Khan (1997)
1998	Daily deviations from the 10-year average maximum and minimum temperature, fungal temperature equivalence function, cumulative fungal temperature function, precipitation, cumulative precipitation, and snow cover averaged for 10-day periods prior to date of inoculum forecast	USA	Eversmeyer and Kramer (1998)
1999	Weather parameters & resistance level of the variety	Argentina	Moschini and Pérez (1999)
2007	**PUCTRI**: Air temperature, relative humidity and precipitation.	Netherland	Rader et al. (2007)
2008	Weather parameters(temperature, RH, precipitation)	Pakistan	Umer et al. (2008)
2014	Night weather conditions i.e. temperature, RH & Rainfall	Europe	El Jarroudi et al. (2014)
2014	Humid thermal ratio (HTR), maximum temperature (MXT) and special humid thermal ratio (SHTR)	India	Kumar (2014)
2015	EPIWHEAT, a generic simulation model based on weather variables, healthy, latent, infectious, and removed sites, and lesion expansion etc	France & Europe	Savary et al. (2015)

(continued)

Table 2.2 (continued)

Year	Parameters taken into considerations	Area/ Country	Reference(s)
2020	Solar radiation, total precipitation, average wind speed, maximum wind speed, minimum air temperature, maximum air temperature, minimum relative humidity and maximum relative humidity	Egypt	El-Orabey and Elkot (2020)
2020	Non linear prediction model (classification regression tree (CART) using night temperature, dew point temperature, relative humidity data	Mexico	Rodriguez-Moreno et al. (2020)

A simulation model was developed for the prediction of brown rust on winter wheat by Rosii et al. (1996) based on the uredospore cycle. The interaction between the host, weather, and infection process were transformed into model parameters by curve fitting, corrections and empirical assumptions. The model was validated by a backward method and the model outputs were compared with actual data collected at eight sites in Italy over 4 years. The model gave a good simulation of the establishment of primary infections of leaf rustand showed 93% accuracy. Air temperature and leaf wetness were identified as the critical factors for infection establishment. Rosii et al. (1997a) developed a simulation model for the development of leaf rust epidemics which blends the two earlier approaches i.e. RUSTDEP (RUST Development of EPidemics) model and WHEGROSIM (WHEat GROwth SIMulation) model. The model simulates the progress of disease severity level, expressed as a percentage of rusted leaf area on individual leaves, over the course of a growing season, with a time step of one day, as a result of the increase in the diseased area caused by each infection cycle. Information about the interactions between stages of disease cycles, weather variables and host characteristics are incorporated into a system dynamic model. The variables used in this model are leaf area with latent infections, infectious leaf area, no longer infectious leaf area, total rusted leaf area, daily increase of RLA, infection efficiency of uredospores (0–1), failure rate of latent infections (0–1), eruption rate of uredia (0–1) and exhaustion rate of uredia alongwith Auxiliary and intermediate variables namely germination of uredospores on leaves (0–1), appresssorium formation (0–1), penetration into leaves (0–1),leaf area (green leaf area), affectable leaf area, leaf area no longer vulnerable to infection, latent period (days), infectious period (days), leaf wetness, wheat growth phase Constants and parameters like maximum leaf area, host effect on DRLA (number < 1), daily mean temperature, hourly temperature, hourly relative humidity and hourly amount of rainfall. This model allows simulating the progress of rust severity well in a wide range of conditions. The hold out method was used for validation and resulted in 80 per cent of the simulated disease severity which fall into the confidence interval of the observed data.

Rosii et al. (1997b) designed an advisory system for the control of leaf rust on winter wheat by combining three simulation models previously elaborated and validated with the networks of weather station, spore collection and field monitoring by combining the three models. The presence of weather conditions conducive to infection establishment is then checked by RUSTPRI (RUST PRimary Infection) model, especially when uredospores could be washed onto the ground by rainfall from the cloud of spores in the air. When the infection might be established, the days when uredia could appear in the field are determined and the technicians take action: they intensify surveys in the pilot-fields to note rust appearance. With disease onset they assess disease severity, as an input for RUSTDEP together with the meteorological data and the simulation from WHEGROSIM. The outputs of epidemic simulation are then used in order to advise growers.

El Jarroudi et al. (2014) made predictions of wheat brown rust infection and progress of the disease based on night weather variables (i.e., air temperature, relative humidity, and rainfall) and a mechanistic model for leaf emergence and development simulation (i.e., PROCULTURE) and used this information to deveop a decision support system.. They also reported that even a single fungicidal application based on the DSS gave a good protection of the upper three leaves incase of susceptible cultivars under field conditions with predominant leaf rust occurrences and the grain yield was not significantly different from that of the plots sprayed twice or thricewith fungicides. Gouache et al. (2015) studied the impact of weather variables on the severity of brown rust in wheat using data from unsprayed plots during 1980–2011. They calculated logistic regressions between theweather parameters derived from the temperature, precipitation, solar radiation and evapotranspiration. They followed the window pane analysis for selecting the weather parameters.. The window algorithm was developed by Coakley et al. (1988) to predict stripe rust severity on winter wheat using weather parameters. The window pane algorithm helps in automatically selecting the weather variables of different overlapping time windows and searches for multiple linear regressions of the variables and the disease severity. With this approach they received a root-mean-squared-error of 0.29 representing 22.4% of occurred disease severity values and a ROC Area Under the Curve value of 0.85. Savary et al. (2015) developed a model known as EPIWHEAT for mapping the epidemics of leaf rust and spot blotch of wheat. This model chiefly included the parameters namely lesion size, lesion expansion, number of infectious sites, temperature, duration of wetness, rainfall and area under disease progress curve for predicting the wheat diseases. Chai et al. (2016) discussed about the use of CLIMEX model to know the global climate suitability for *P.triticina* causing leaf rust of wheat. The distribution of leaf rust is strongly influenced by land use in terms of host availability and irrigation. In this CLIMEX model the parameters were fitted based on the biology of leaf rust pathogen and adjusted according to its known distribution using natural rainfall scenario/irrigation schedule. Garin et al. (2018) made an effort for modeling interaction dynamics between two foliar pathogens of wheat i.e. Septoria blight and leaf rust because both the fungi have contrasting traits in terms of colonization of leaf tissues and of spore dispersal. This modeling framework comprised of three sub-models:1.geometric model of lesion growth and interactions at the leaf scale; 2: model of lesion growth with global interactions at leaf scale 3: epidemiological model with interactions at canopy scale. They found that the simulated epidemics of brown rust were greatly affected by the presence of septoria, but the reverse was not the case. A weather based approach to predict leaf and stripe rust in winter wheat has been deployed by Rodríguez-Moreno et al. (2020). They used Classification and regression trees (CARTs) for data analysis, in which an hourly weather variables data, and a 3 year field disease data of winter wheat rust were integrated to forecast the presence/absence of pathogens. Theyobserved the association of leaf rust severity with a night temperature of <14.25 °C and global radi-ation of <521.67 Wm^{-2}, while the estimated dataset showed that its severity is better explained by the dew point temperature of <13.7 °C and a mean temperature of <19.06 °C. The analysis indicated the pathogen's preference for non-dry ambient conditions and the preference of stripe rust pathogen for humid and warmer temperatures than leaf rust.

2.2.3 Stem Rust of Wheat

Eversmeyer et al. (1973) predicted the severity of stem rust by weekly and commulative number of uredospores deposited per cm^2, cultivar, growth stage of the crop, minimum and maxiumum temperature, fungal temperature growth function and fungal infection function. They used the stepwise multiple regression analysis to find out the meterological and biological factors responsible for variation in stem rust sverities. In India, detailed studies have been conducted by Nagarajan and his co-workers for the prediction of stem rust of wheat. The important ones like "Indian stem rust rules"; a set of synoptic conditions for prediction of setm rust was given by Nagarajan and Singh (1975) as described under:

1. A storm/depression should be formed either in the Bay of Bengal or in the Arabian Sea between 65°--85°E and 10°--15°N and should dissipate over central India.
2. A persistent high-pressure cell must be present over south-central India (not far from the Nilgiris).
3. A deep trough extending up to south India and caused by the onward movement of a western disturbance should occur. If one or a combination of these conditions is satisfied, it is likely that uredospores will be transported to central India and deposited there in rain.

For predicting infections of wheat stem rust 20–25 days before the appearance of the disease on the crop a method was also described by Nagarajan and Singh (1976) in which the application of linear equations aided in the local decision making for successive disease management operations in the likely areas and times of disease appearance are known. Based on field epiphytotic studies, a linear model for prediction of stem rust severity 7 days in advance was developed by Nagarajan and Joshi (1978):

$Y = -29.373\ 3 + 1.820\ Xx + 1.7735\ X2 + 0.2516\ X3.$

where Y = expected disease severity after 1 week,

Xx = mean disease severity for the past week,

X2 = mean weekly minimum temperature (°C) expected for the next week,

X3 = mean maximum relative humidity expected in the next week and –.
29.373 3 is a constant.

This model was further tested by multilocation test (Karki et al. 1979). Hernandez Nopsa and Pfender (2014) developed a latent period duration model for stem rust of wheat. They formulated a mathematical model to predict latent period duration based on temperature, the model can be applied to data consisting of varying temperature readings measured at any desired time increment and can help in estimating epidemic development, and also in improving understanding epidemiologyof stem rust. Recently many modelers have tracked the spore transport events and spread probabilities in case of stem rust in different parts of the world (Meyer et al. 2017; Visser et al. 2019). Prank et al. (2019) made certain attempts to study the impact of climate change on spread potential of stem rust and reported that warmer climate with lower relative humidity and enhanced turbulence will lead to∼40% increase in the urediniospore emitting potential of an infected field as global average. Allen Sader et al. (2019) developed an early forewarning system for mitigation of stripe and stem rust of wheat in Ethopia. The EWS comprised of a sophisticated framework which integrates field and surveillance data, spore dispersal and disease environmental suitability forecasting and further communicatethe information to policy-makers, advisors and smallholder farmers. The system involves daily automated data flow between two continents during the wheat season in Ethiopia. The system works oninter-disciplinary approach (biology, agronomy, meteorology, computer science and telecommunications). This EWS is the first system which combines near real-time field survey observations, advanced numerical weather prediction (NWP) meteorological forecast data, Lagrangian spore dispersion forecasts along with detailed environmental suitability model forecasts, and wide-ranging communication methods to predict near real-time risks of disease occurrence in a developing country context.

Mulatu et al. (2020) developed a nonlinear modelfor prediction of stripeand stem rust based on historical weather and disease data during 2010 to 2019. The weather variable such as daily rainfall, temperature (minimum & maximum) and humidity were used. The intial disease incidence and severity were assessed at 3 days interval and the data was combined with mean values of weather parameters and correlation was worked out. The presence or absence of the disease was predicted using WEKA software machine learning tool with J48 decision tree algorithm for data analysis. J48 un-pruned decision tree algorithm and J48 pruned decision tree algorithm were used respectively to develop stripe rust and and stem rust prediction model.

2.3 Karnal Bunt

Karnal bunt (KB) is an important disease of wheat caused by a fungal species *Tilletia indica* Mitra. Eventhough Karnal bunt is a minor disease but it is always significant with respect to its quarantine importance worldwide. Besides, soil, seedas well as air borne nature of the fungus makes its management quite difficullt (Mitra 1937; Mundkur 1943; Bedi et al. 1949). In India, the germination of teliospres took place from the middle of February to the middle of March under optimum temperature (18–25 °C) and relative humidity (>70%) to produce primary sporodia (Mitra 1937; Mundkur 1940; Holton 1949; Krishna and Singh 1981). The secodary sporidia are produced by primary sporidia which are air borne and lodge onto plant surfaces by air currents and rain splash or monkey jumping of sporidia from the soil surface to the ear heads. They may germinate and produce additional generations of secondary sporidia on the wheat heads and cause infection (Bedi 1989; Bains and Dhaliwal 1989; Dhaliwal and Singh 1989; Gill et al. 1993; Nagarajan et al. 1997). Wheat spikes are susceptible from early head emergence to late anthesis (Duran and Cromarty 1977; Warham 1986; Bondeet al. 1997). Sporidial germ tubes penetrate through stomata of glumes, lemmas and palea. In some cases, there may be direct penetration of immature seed (Aujla et al. 1988; Dhaliwal et al. 1988; Goates 1988; Salazar-Huerta et al. 1990). The various stages of the life cycle of the fungus right from the initiation till the development is highly dependent on suitable weather conditions during flowering which is most susceptible stage to infection. There are number of studies which proved the effect of weather parameters on different stages of life cycle of the fungus *Tilletia indica* (Purdy and Kendrick 1957; Munjal 1975; Bains (1992); Bansal et al. 1983; Zhang et al. 1984; Smilanick et al. 1985; Aujla et al. 1986; Singh 1986; Dhaliwal and Singh 1989; Smilanick et al. 1989; Aujla et al. 1990; Bedi et al. 1990; Schall 1991, Ratan and Aujla 1992; Gill et al. 1993; Singh and Aujla 1994; Nagarajan et al. 1997; Kaur et al. 2002a; Sharma and Nanda 2002; Sharma and Nanda 2003; Murray 2004, Goates and Jackson 2006; Sansford et al. 2008; Bedi 1989; Dhaliwal and Singh 1989; Bains and Dhaliwal 1989; Siddhartha et al. 1995).

If we know the exact weather parameters, the disease can be easily controlled by chemicals (Sharma et al. 2004). Various studies have been conducted in this regard (Table 2.3) and most of them are from India. Intitally, the role of high humidity, low temperature, continuous rainy/foggy and cloudy weather from ear emergence to anthesis have been reported to be responsible for disease epiphytotics in different years at many places (Munjal 1971; Aujla et al. 1977; Singh and Prasad 1978).

In a comparative study of KB epiphytotic years and KB free years it was indicated that more number of foggy days, reduced sunshine hours and rainfall during flowering stage were the characteristics of epidemic years. On the basis of this analysis, thumb rule to forecast the disease in endemic areas was postulated by Aujla et al. (1991) as described in Table 2.3. Number of rainy days at flowering stage in February at Mexico was found to be positively correlated while the amount of rainfall showed weak positive relation and temperaturehad negative coorelation with Karnal bunt incidence (Nagarajan 1991). Multiregression Model based on dfferent weather parameters was developed and Karnal bunt infection can be predicted using multiple regression models with reasonable reliability (Mavi et al. 1992; Singh et al. 1996). Jhorar et al. developed a disease prediction model for Karnal bunt disease on the basis of 20 year data. In their study HTI (Humid Thermal Index) was generated as a single compound variable for more than 90% disease variation fitting a quadaratic function. Smiley (1997) stressed the importance of suitable rain and humidity events and defined conditions for Karnal bunt occurrence. Both the models

Table 2.3 Weather parameters/models for development of Karnal bunt over the years

Parameters/Models	Specific Conditions/ Equations	Year	Country	References
Relative humidity (RH), temperature, continuous rainy / foggy and cloudy weather from ear emergence to anthesis	Humiditymore than70% low temperature (19–23 °C), continuous rainy / foggy and cloudy weather for >13 days	1971–1978	India	Munjal (1971), Aujla et al. (1977), Singh and Prasad (1978)
Cloudy weather, temperature, relative humidity and rains during last week of February	At heading satge, 1) sky remained overcast, 2) temperature was 15–22 °C, 3) RH >40% and up to 80% and high showering	1991	India	Aujla et al. (1991)
Number of rainy days, amount of rainfall and high temperature in February	–	1991	Mexico	Nagarajan (1991)
Humid thermal index (HTI) Evening relative humidity (ERH) Maximum temperature (TMX)	HTI = ERH/ TMX Disease incidence (DI) = −0.85 + 1.5 HTI	1992	India	Jhorar et al. (1992)
Multiregression model based on maximum temperature (Tmax), sunshine duration (SSD), evening relative humidity (RHe) and rainy days (RD)	Plant disease incidence (PDI) =4.12–0.10*Tmax +0.10*RHe-0.115*SSD + 0.076*RD	1992	India	Mavi et al. (1992)
Multiple regression model using different weather parameters	–	1996	India	Singh et al. (1996)
Suitable rain and humidity events	1) more than 3 mm rain on each of two or more successive days, 2) at least 10 mm being collected within the 2 days interval and 3) more than 70% average daily RH during both rainy day	1997	USA	Smiley (1997)
Humid thermal index (HTI) and suitable rains events (SRE)	–	2002	Australia	Stansbury and McKridy (2012)
Temperature, rainfall amount and frequency	Z = 6.6X1–9.45X2–1.12X3, X1 is average maximum temperature, X2 is	2008	Texas	Workneh et al. (2008)

(continued)

Table 2.3 (continued)

Parameters/Models	Specific Conditions/ Equations	Year	Country	References
	average rainfall amount, and *X*3 is average rainfall frequency for the 18-day period			
GeoPhytopathology model (GPMTI) based on HTI	HTI = ERH/TMX ($5 \leq T \leq 35$ and $60\% \leq RH \leq 95\%$), HTI = 0 ($T < 5$ or $T > 35$ or $RH < 60\%$ or $RH > 95\%$)	2010	China	Wei-chuan and Gui-ming (2010)
Total rainfall in the month of march and evening relative humidity of February	DI = 6.873(0.0962 (FmT)-0.132 (FmxT)-0.34 (Frhm)-0.056((Frhe) + 0.040(Mtrf) + 0.065 (MmxT)-0.132(MRd)	2015	India	Bala et al. (2015)
Rainfall frequency, total rainfall and HTI during susceptibility period i.e. ear head emergence to anthesis stage	LogitY = −5.245 + 0.0279total rainfall = 0.0449 rainfall frequency/rainy days +0.239 heat thermal index	2016	India	Singh and Karwasra (2016)

developed by Jhorar et al. (1992) and Smiley (1997) were compared by Stansbury and McKridy (2012). They suggested that data on HTI and SRE (Suitable Rains Events) during the susceptible period every year may be more suitable in determining climatic suitability for Karnal bunt in comparison to long term, average data. Workneh et al. (2008) again used temperature, rainfall amount and frequency to predict the disease in Texas. An HTI based GeoPhytopathology Model was developed by Wei-chuan and Gui-ming (2010) in China. Recently, total rainfall, evening relative humidity was defined as the most critical factors for KB development. The model resulted in a coefficient of determination of 0.88 and D. W value of 1.54 (Bala et al. 2015). Singh and Karwasra (2016) established a significant correlation between KB infection and rainfall frequency (0.71), total rainfall and HTI for identifying the KB positive and KB negative crop seasons during susceptibility period i.e. ear head emergence to anthesis stage.

All these studies indicated that there is an unexplained variation in Karnal bunt incidence over the periods. Variable environmental conditions over the periods at the susceptible stage of host may result in such variations in Karnal bunt incidence. However, such variation has also been observed under artificially epiphytotic conditions created for screening of germplasm. This suggests that several other aspects of pathogen biology i.e.inoculum threshhold level, pathogen fitness at every stage and probability of encounters between compatible sporidia may also contribute to disease escape or variation in Karnal bunt incidence over the period.

2.4 Fusarium Head Blight

Fusarium head blight is an important disease of cereals which mainly affects wheat, barley, corn and oats (Schmale and Bergstrom 2003). It is the second biggest disease problem in USA, Canada and parts of South America (Savary et al. 2019) and is also known by names such as wheat scab, head scab or simply scab. It affects floral ear heads and is primarily caused by *Fusarium graminearum* Schwabe [teleomorph *Gibberella zeae* (Schwein.) Petch] (Parry et al. 1995). Around 17 species of *Fusarium*, are known to be associated with FHB; *Fusarium culmorum*, *Fusarium avenaceum* (*Gibberella avenacea*), *Fusarium poae*, *F. oxysporum*, *F. pallidoroseum* and *Microdochium nivale* (*Monographella nivalis*) being the predominant ones (Parry et al. 1995; Kaur 1998; Saharan and Sharma 2009; Panwar et al. 2016).

The disease was first described by Smith (1884) in U.K. Its epidemic was reported in the same year in U.K. and *Fusisporium culmorum* now known as *Fusarium culmorum* was found associated with it (Ghimire et al. 2020). In later years, the epidemics also occurred in USA where heavy losses were observed in 1917, 1919, 1928, 1932 and 1935 (Stack 2003). It caused havoc in Paraguay in 1972 and 1975 (Viedma 1989); south-eastern region of Argentina in 1963, 1976, 1978 and 1985 (Moschini et al. 2004) and several states of USA and Canada in 1993 (Nganje et al. 2004). Later on severe outbreaks of the disease occurred all around the world where high rainfall and humidity persists during the wheat season. It was reported to occur in moderate to severe intensity in China (Zhuang and Li 1993) and India (Roy 1974; Singh and Aujla 1994). The disease is favoured by wide range of temperatures depending upon the species involved. *Microdochium* sp. is common in temperate climate while *F. graminearum* require comparatively higher temperatures (25–30 °C) along with persistent high moisture and rains (Teli et al. 2016). *F. culmorum*, *F. avenaceum*, *F. poae* thrive more in cool temperatures of around 20 °C (Parry et al. 1995; Kaur et al. 1999).

Fusarium head blight of wheat is a minor disease in India. But, since nineties it has started appearing in Punjab, where it is more severe on durum wheat as compared to bread wheat. Epidemic of the disease occurred in 1995–96 and 2004–05 in sub-mountainous districts of Punjab due to frequent rains resulting in more than 90 per cent infected heads in PDW 274 (Bagga and Saharan 2005). Most of the wheat varieties have limited resistance to FHB (Kharbikar et al. 2019).

It can result in crop losses as high as 70 per cent under epidemics (Moschini et al. 2004). In North America, it resulted in loss of 7.7 billion US dollars from 1993–2001 (Nganje et al. 2004). Under artificial epiphytotic conditions, FHB can result in yield losses of up to 21.6% in PBW 222 wheat variety (Kaur et al. 2002b). Besides yield loss, it results in food and feed contamination due to production of mycotoxins. Deoxynivalenol (DON) is the most common associated mycotoxin present in grains infected with this fungus (McMullen et al. 1997; Desjardins 2006; Dweba et al. 2017), the MRLs for which have been fixed at 1 ppm in finished products and 5–10 ppm for livestock feed (FDA 2010). Thus, it has become the biggest cause of concern associated with this disease.

Epidemiological parameters affecting FHB have been described by several workers (Kaur et al. 1999; Osborne and Stein 2007; Molineros 2007; Bolanos-Carriel 2018). The disease in the field is favoured by 48–72 h of high relative humidity (90%) along with temperatures between 15–30 °C. Infection efficiency reduces significantly when these conditions are not met. Perithecia can develop between 9–29 °C, with an optimal temperature around 22 °C. Sexual reproduction is limited at temperatures of more than 30 °C. Relative humidity is a crucial component for development and maturation of perithecia (Dufault et al. 2006). It required an optimal barometric pressure of less than −50 bars (−5Mpa) (Sung and Cook, 1981), rainfall of more than 5 mm for its development (Inch 2001). Perithecia bear 3-septate ascospores which are hyaline and 19–24 × 3–4 μm in size (Booth 1971). Ascospores are produced at a temperature of 25–28 °C under ultraviolet light (Sutton 1982). Macroconidia of *F. graminearum* are produced in a temperature range of 28–32 °C (Keller et al. 2013), while temperatures below 16 °C or above 36 °C are detrimental. Under dry conditions, *F. graminearum* produces perithecia while macroconidia is produced under wet conditions (Sung and Cook 1981).

Extensive work has been carried out all over the world to develop and test weather-based forecasting models of FHB (Table 2.4). A sizeable amount of information has been generated to predict mycotoxin associated with FHB (DON) in wheat grains. The models are generally formulated considering the relative importance of components of disease triangle in a manner which gives best fit for disease risk assessment (McCown 2002). Estimation of a disease in any moment of time is essential to predict the outcome in a crop production program. It helps us to cover our weak points in the crop growth season, which could be due to any living or non-living reasons. The corrective actions integrate into a decision support system. The principle involved here is that life cycles of diseases proceed in certain well defined manner which can be predicted with great accuracy if long term disease and weather data is available. Based on predicted critical points in disease development, a farmer can go for management practices with optimal fungicide doses (Landschoot et al. 2013). Timely and accurate identification of plant diseases is another aspect of decision support system which can counter disease in environment friendly and cost effective way (Thandapani et al. 2019).

For fusarium head blight, there can be two lines for developing models, first based on predicting disease or presence of scabbed grains at harvesting and the second is predicting the mycotoxin (DON) in mature grain at/after harvesting. Several weather based models have been developed all around the world for predicting FHB, but most of these are site and year specific. Because of their specificity to region for which they have been developed, only few FHB models could be used in other regions. Italian, Argentinean, and Canadian models have been adjusted for other crop conditions and even used in countries outside their region of origin (Moschini et al. 2004; Del Ponte et al. 2005; Schaafsma and Hooker 2007).

Forecast models have been developed and validated in United States (De Wolf et al. 2003; De Wolf and Isard 2007; McMullen et al. 2012; Shah et al. 2013; Shah et al. 2014), Canada (Hooker et al. 2002; Schaafsma and Hooker 2007; Giroux et al. 2016), Belgium (Landschoot et al. 2013; Hellin et al. 2018), Netherlands (Franz et al.

Table 2.4 Disease prediction models developed globally for Fusarium Head Blight and Septoria blight of wheat

Year	Equation	Parameters taken into considerations	Area/ Country	References
Fusarium head blight				
2002	DON = exp.[−2.15 + 2.21RAINA – 0.61 $(RAINA)^2$ + 0.85RAINB + 0.52RAINC – 0.30TMIN – 1.10TMAX] – 0.1	Rainy days (>5 mm), temperature (< 12 °C or > 32 °C) 7–10 days before and after heading	Canada	Hooker et al. (2002)
2003	$TRH9010 = Logit(p^*) - \beta_0/\beta_1$ Model A	Temperature (15–30 °C) and humidity (hrs. Of >90%) after flowering	USA	De Wolf et al. (2003)
	$TRH9010 = Logit(p^*) - \beta_0/\beta_1 T15307$ Model B Where, $T15307 = Logit(p^*) - \beta_0 - \beta_1 DPPT7/\beta_2$	Temperature and humidity variables 7 days prior to flowering		
2003	Risk of DON presence in kernels R-tox = $-6.915 + X_{1,n} + X_{2,n} + X_{3,n} + X_{4,n} + X_{5,n} + X_{6,n}$	Temperature, rainfall, leaf wetness duration and relative humidity Different crop management practices	Italy	Rossi et al. (2003)
2004	$\boldsymbol{PI\%} = 20.37 + 8.63\ \boldsymbol{NP} - 0.49\ \mathbf{n}\boldsymbol{DD}$ $R^2 = 0.86$	Rainfall (>0.2 mm), humidity (>81%), 8 days before heading till accumulation of 530 degree days n*DD* = daily residuals obtained by subtracting 9 to the minimum temperature and the exceeding amount of maximum temperature from 26 °C	Argentina	Moschini et al. (2004)
2005	DONcast	Rainfall and minimum temperature 4–7 days before and 3–10 days after heading	Canada	Schaafsma and Hooker (2007)
2013	Base.0:Logit (μ) = $\beta_0 + \beta_1 res1 + \beta_2 res2 + \beta_3 res3$ Base.1:Logit (μ) = $\beta_0 + \beta_1 res1 + \beta_2 res2 + \beta_3 res3 + \beta_4 wc2 + \beta_5 wc3$ Base.2:Logit (μ) = $\beta_0 + \beta_1 res1 + \beta_2 res2 + \beta_3 res3 + \beta_4 TYPE$	Temperature and relative humidity	USA	Shah et al. (2013)
Septoria blotch of wheat				
2003	$S_{GS75} = 4.37(1.01)Wet_{Nod;80}[62,17] + 3.12(1.48) Tmin_{Cnod;7+}[145,70] + 2.78(1.26)$	Average wind speed [78,25], average leaf Wetness [57,22], number of days with minimum	U.K.	Pietravalle et al. (2003)

	$Rain_{Nod;9}$[81,61]-6.4(2.7) Adj.R^2 = 0.77 S_{GS75} = 13.8(1.5)$Rain_{Nod;9}$[60,37] + 6.1(2.8) Adj.R^2 = 0.86	temperature less Or equal to 7 °C [190,70], and number of consecutive days with minimum temperature less or equal to 7 °C [190,70]		
2009	$Model^e : 0.046 \times Rain + 0.042 \times T_{min} - 6.69 > 0$ $Model^f : p = {}^{1}\!/\!_{1+e^{4.38-0.22\times Rain-0.032\times T_{min}}}$	Rainfall and temperature	England	Beest et al. (2009)
2016	CRI Y = 20.00 + 8.90Z1,1 + 3.11Z2,1 + .005Z12,1 Tillering Y = 97.45 + 0.58Z1,1 + 2.87Z2,1 – .004Z12,1 Jointing Y = 100.8 + 2.29Z1,1 + 0.87Z2,1 – .029Z12,1 Flowering Y = 37.41 + 0.87Z1,1 + 0.34Z2,1 + .008Z12,1 Milking Y = 101.0 + 1.21Z1,1 + 0.78Z2,1 – .014Z12,1 Dough Y = 132.5 + 0.96Z1,1 + 0.68Z2,1 + .002Z12,1	Maximum temperature, maximum relative humidity and their interaction	India	Pant et al. (2016)
2017	$Y = [(36\text{-}T)/7] \times [(T\text{-}16)/13]^{1.8571} \times [1\text{-}(0.8114)^{D\text{-}m}]$	Minimum relative humidity duration (m) of 9 h produced lesions Temperature (T) and RH-duration (D) affected Daily infection index (Y)	India	Viani et al. (2017)
2019	Model B $TPC(T) = \frac{1}{LP_{min} + Curv\ X\ (T - T_{opt})^2}$	Temperature and latent period LP_{min} = minimum latent period, T = mean canopy temperature, T_{opt} = optimal mean leaf temperature	U.K.	Chaloner et al. (2019)

2009; Van Der Fels-Klerx et al. 2010), Switzerland (Musa et al. 2007), Italy (Rossi et al. 2003; Prandini et al. 2009), China (Zhao and Yao 1989), Argentina (Moschini et al. 2004) and Brazil (Del Ponte et al. 2005).

In United States, five weather based logistic regression models for FHB were developed which could predict Fusarium head blight epidemics with accuracy of 62–85 per cent using predictor variables in narrow time periods around crop anthesis (De Wolf et al. 2003; Haran et al. 2010; Peel et al. 2007; Shah et al. 2013; Shah et al. 2014). The models used precipitation hours, time duration of temperature remaining between 15–30 °C, pertaining to period of 7 days prior to anthesis (Z65) and the duration when temperature remained between 15–30 °C along with relative humidity of 90 per cent.

De Wolf et al. (2003) were associated with development of 10 regression models which could predict epidemics. Models A (TRH9010) requires temperature and humidity combination variables in post flowering phase. Models B, C and D required the interactions of weather parameters during pre and post flowering phase of the crop to predict FHB. Models C and D had high prediction accuracy of more than 90 per cent under, when FHB severity remained low ($<10\%$) but, in epidemics ($>10\%$ severity) the accuracy dipped to less than 73%. The authors however emphasized three models A, B and I (DPPT7). The first model set (DPPT7: I) utilized rainfall hours during 7 days to flowering, the second set of models (T15307: B and I) used hours when temperature remained between 15–30 °C, in 7 days period before flowering while the third set of models (TRH9010: A and B) required hours with both relative humidity of more than 90 per cent and temperature between 15–30 °C 10 days post flowering. These models can forecast an epidemic if critical predicted probability reaches or exceeds 0.5, as per the algebric equations (Table 2.4). Molineros (2007) redefined the De Wolf et al. (2003) by using only average relative humidity of 7 days prior to flowering and four levels of varietal susceptibility.

Shah et al. (2013, 2014) in their three logistic regression models (Base 0, Base.1 and Base.2) which included resistance predictor besides weather-based variables like temperature, rainfall and relative humidity values within 15 days around flowering. Relative humidity was found better at characterizing moisture effects on FHB than rainfall in these models and therefore except one RHR.RHG90nR.PRE7.24H, rest all used only temperature and relative humidity predictors. The predictors were the combinations of t and rh in different observation periods, pre- or post-flowering. Unlike previous models, they considered 24-h day period from 08:00 to 08:00 instead of midnight to midnight cycle. All models we developed contained four or fewer weather-based predictors. Fifteen model sets based on both logistic and additive logistic regression models were selected by the authors when model selection protocols were applied different combinations of base models and weather parameter periods. Five models were developed from base.0, four from base.1 and six from base.2. Seven models out of fifteen were based on pre-flowering weather predictors (7, 10, 14 and 15-day window) while remaining used post-flowering (5, 7 and 10 days) data. These models made fewer misclassification errors than models deployed in US.

In Canada, a weather based prediction model was developed by Hooker et al. (2002) to access DON content (ppm) in grains based on weather parameters existing in three time zones near to heading i.e. Z58 stage of wheat crop, represented in three equations. This empirical model was based on predicting DON content (in ppm) at harvest with different equations related to three time periods around heading (Z58). Rainfall and temperature were identified as crucial meteorological parameters in three time zones (1) 4–7 days before heading (2) 3–6 days and (3) 7–10 days after harvesting. Time period, 4–7 days before and 3–10 days after heading, were found to contribute maximum in predicting DON in grains. Before heading period helped in inoculum build up and DON content was positively correlated with rainy days (>5 mm rainfall) and inversely related to daily minimum air temperatures (<10 °C). Post heading period influenced flower infection. Here, DON was positively correlated with number of rainy days and days with relative humidity of over 75 per cent at 11:00 h while it negatively correlated with maximum daily temperature (>32 °C) and average temperature (<12 °C). Number of rainy days exceeding 5 mm per day and temperature below 10 °C, 4–7 days before heading could determine DON in 55 per cent of fields as per following equation.

1. $\mathrm{DON} = \exp.[-0.30 + 1.84\mathrm{RAINA} - 0.43\ (\mathrm{RAINA})^2 - 0.56\mathrm{TMIN}] - 0.1.$
   Where, DON = concentration of DON ($\mu g\ g^{-1}$),
   RAINA is the number of days of rain >5 mm day^{-1} 4–7 days to heading.
   TMIN is the number of days of temperatures <10 °C 4 and 7 days before heading.
   Weather variables observed from 7 days before heading to 10 days after harvesting could justify DON content in 63–79 per cent of events. The prediction equations involved additional variables of RAINB (no. of days of rain >3 mm per day, 3–6 days after heading), RAINC (no. of days of more than 3 mm per day 7–10 days after heading) and TMAX (days with more than 32 °C temperature).
   If RAINB is positive value, then model mentioned in Table 2.4 explains the DON content but, when RAINB is 0, then
2. $\mathrm{DON} = \exp.(-0.84 + 0.78\mathrm{RAINA} + 0.40\mathrm{RAINC} - 0.42\mathrm{TMIN}) - 0.1.$
   These models could predict with high accuracy in case the DON content remain low to moderate. However, it failed to predict in case of epidemics.

Modification in continuation to above model came as DONcast which was released commercially in Canada (Schaafsma and Hooker 2007). It predicted DON in harvested grains using meteorological variables in five distinct time zones around heading (Z58) instead of three in Hooker et al. (2002). In addition, it also worked in maize for DON and fumonisins. Total rainfall (mm); daily average, minimum, and maximum temperature (°C); and relative humidity are used singly or in combination to make predictions in this model. Wheat variety, crop rotation and tillage were found to influence DONcast predictions. Robustness of this model lied in the fact that it could predict DON across diverse environments. Accuracy of prediction of DON content was as high as 72 and 83 per cent in case the content stayed around 1.0 mg/kg and 2.0 mg/kg, respectively in France, while the corresponding figure for prediction accuracy in Uruguay were 68.3 and 74.8 per cent, respectively. In Netherlands, DONcast regression equations could predict DON content with an accuracy of 44.7 per cent for the threshold value of 1250 μg/kg (Franz et al. 2009). Overall, this model could explain DON content with an accuracy of 72 per cent in case the content stayed around 1.0 mg/kg in more than 1000 fields of wheat from four countries over a period of 10 years.

Giroux et al. (2016) in Canada reported two American (De Wolf et al. 2003) and one the Argentinean (Moschini et al. 2001) forecasting models to work accurately, with high sensitivity and specificity under Quebec conditions when the thresholds were adjusted using the results for the ROC curve analyses. Weather-based models predicting FHB incidence and DON in Italy did not work in Canada. DON content (1 ppm) was best crop damage indicator to differentiate epidemics and non-epidemics. The models which captured pre- and post-flowering weather attributes (De Wolf et al. 2003) worked well as compared to ones which used only pre-flowering weather data (Molineros 2007). Thus, flowering stage is the critical point, which if missed can lead to decreased effectiveness of a model (Giroux et al. 2016). All these empirical models predict the infection risks with simple polynomial equations, which are easy to develop and can be used for predicting FHB with adequate accuracy. Higher complexity models means more accuracy but at the cost of difficulty in adaptation to new regions other than for which it has been developed (Prandini et al. 2009; Rossi et al. 2010). DONcast and Hooker prediction models from Canada and Rossi inf and Rossi tox from Italy with prediction sensitivity of 60, 60, 53, and 40 per cent, respectively were not much effective as they would not advocate FHB control even if the weather is favourable for the disease. De Wolf I model from the United States gave sensitivity and specificity of 6.7 and 64.9 per cent, which meant that disease management warnings will be absent despite high risk conditions or control strategies, may be recommended in the absence of disease.

In Belgium, Landschoot et al. (2013) extensively evaluated the performance of five regression techniques (multiple linear regression, ridge regression, regression trees, gradient boosting and support vector machines) and four cross-validation strategies (random *K*-fold cross-validation, cross-year cross location, cross-year validation, and cross-location validation) to predict Fusarium head blight (FHB) in winter wheat. The authors developed procedures to obtain an unbiased performance of the model during its development phase itself, before its actual release thus paving way for robust models which can work in new locations and different years from the years and locations based on which it has been developed. Furthermore, advanced predictive models developed in areas like data mining and machine learning were able to outperform traditional multiple linear regression models to a great extent. In subsequent years, models were developed which correlated air-borne inoculum (macroconidia and ascospores) quantified with TaqMan qPCR assay with FHB infection ($R = 0.84$) and DON content ($R = 0.9$) in the grains (Hellin et al. 2018).

DONcast model developed by Hooker et al. (2002) could not give accurate prediction in most of the cases, when applied in Netherlands. Franz et al. (2009) formulated two prediction models 1 and 2 for DON content for Netherlands agro-climatic conditions by considering 24 days pre- and post-heading dataset in formal and 6 days around heading in later model. Both the models predicted DON content in mature Dutch winter wheat with high accuracy. Higher DON content was observed when temperature increased from 15 to 25 °C, increase in precipitation from normal and high relative humidity. The disease and DON content in grains reduced if temperature went above 25 °C. Model 1 with coefficient of determination of 0.59 between observed and predicted values and sensitivity of 63 per cent performed better than model 2. The authors also observed high disparity in DON levels in different regions of Netherlands although there was no significant difference in meteorological variables or infection pressure.

A neural network model for prediction of Deoxynivalenol was designed in Czech Republic taking continuous variables of average temperature and total precipitation in April, average temperature and total precipitation 5 days prior to flowering and categorical variable of the preceding crop (Klem et al. 2007). This neural network model gave high correlation ($R^2 = 0.87$) between observed and predicted data.

Weather based mechanistic model for FHB (*F. graminearum* and *F. culmorum*) infection and mycotoxin contamination was developed in Italy, which was applied successfully over a commercial scale as a decision support system (Rossi et al. 2015). The model is based on calculation of daily infection index (FHB-inf) and daily mycotoxin accumulation index in wheat kernels (FHB-tox). The index of infection risk varies between 5 and 35 and the index of accumulation of toxins is generally between 0 and 2. The infection prediction model uses average temperature, number of hours where relative humidity stayed above 80 per cent, total precipitation (in millimeters), and the intensity of rainfall from heading (Z58) until harvest. The model retains cumulative daily FHB-inf and FHB-tox index for each *Fusarium* species till harvesting of the crop. The model was validated in Italy (Rossi et al. 2006) and Netherlands (Camardo Leggieri et al. 2013) with 90 per cent accurate DON predictions, while in Egypt, U. K., Mexico, Hungary and Russia, the prediction accuracy was around 60 per cent (Battilani et al. 2013; Camardo Leggieri 2012; Camardo Leggieri et al. 2011). This FHB model was later included in a Decision support system granoduro.net® (Ruggeri 2014), which provides outputs in real time to farmers via a web-based user interface.

In Argentina, *Fusarium graminearum* is the main pathogen associated with fusarium head blight (Carranza et al. 2002). Moschini et al. (2013) reported an empirical model forecasting head blight/deoxynivalenol and its spatial distribution, supported by land and remote sensing data in the Pampas region. The model considered thermal amplitude instead of relative humidity took into comparison the past (1961–1990) and future (2071–2100) climate to train their model.

Two-day periods when rainfall exceeded 0.2 mm and relative humidity remained above 81 per cent on first and 78 per cent on second day, showed high relation with disease incidence ($R^2 = 0.81$). Weather variables and FHB incidence had high correlation starting from 8 days before heading till accumulation of 530 degree days (*DD*) (Table 2.4).

$PI\% = 20.37 + 8.63\ NP - 0.49\ \mathrm{n}DD$

$R^2 = 0.86$

With the same data another model was developed that required only maximum and minimum temperature and rainfall.

$PI\% = -9.15 + 6.47\ ND + 0.35\ pDD$

$R^2 = 0.81$

Where, *ND* is number of consecutive days with rainfall and thermal amplitude (difference in maximum and minimum temperature) should be less than 7 °C; *pDD* is accumulating residuals of more than 9 °C in minimum temperature, on days when maximum and minimum temperature is less than 25 °C and more than 9 °C, respectively.

Predicted Fusarium index (PFI %) was obtained from (a) and (b)

(a) being observed daily progress of anthesis (% of wheat heads with exposed anthers).

(Anther, values from 0 to 1) and the time in degree days (DD_{12}: daily accumulation of average daily temperature above 12 °C)

$LogitAnther = -6.765052912 + 0.136395967\ DD_{12} - 0.000694621\ DD_{12}^2 + 0.000001384\ DD_{12}^3 - 0.000000001\ DD_{12}^4$

(b) Predicted severity (PS %): in controlled environment with conidia exposed to different wetness period and temperature during wetness period.

$LogitS = 38.77166158 - 0.53815698\ W - 6.02985565\ T_W + 26{,}849{,}793\ T_W^2 - 0.00396097 T_W^3 + 0.04990941\ I_1 - 0.00092343\ I_2$

A day with rainfall of at least 0.2 mm and relative humidity of at least 81 per cent is considered for assigning the value of *W*. A single day is represented as $W = 24$ h, while two or three consecutive days means $W = 48$ and 72 h, respectively. T_W depicted temperature during wet day. Final *PFI* % was obtained by adding the partial products between (a) and (b) dividedby 100.

As the crop response to FHB varies with genotypes having different ear head characteristics and even the same genotype may respond differently over years under prevailing weather conditions (McMullen et al. 1997). Therefore, availability of regular and precise weather data is the absolute requirement for any model to work accurately (Solis and Flores 2003). Moschini et al. (2013) could successfully use the model for locations lacking meteorological data by substituting the missing weather inputs from satellite and remaining from interpolated weather station data. Rainfall and temperature data, respectively were sourced from Tropical Rainfall Measurement Mission (TRMM, 3B42 product) and climatic zoning based on NOAA-AVHRR images to predict FHB with adequate accuracy.

Nicolau and Fernandes (2012) in Brazil devised a Hierarchical Autoregressive Binary Data Model (HARBDM) to predict daily inoculum levels (spore density), deposition probability of airborne spores of *Gibberella zeae* and probable incidence of FHB. Rainfall and relative humidity positively correlated while sunshine hours were associated negatively with spore prevalence in air. Temperature had weak association with spore incidence.

Several other models have been put to use for farmers through online interactive systems such as Fusarium Risk Tool in USA available at http://www.wheatscab.psu.edu/; FusaProg in Switzerland available at https://www.fusaprog.ch/ (Musa et al. 2007) and granoduro.net available through http://www.horta-srl.com at https://www.horta-srl.it/sito/portfolio-item/granoduro-net/ (Rossi et al. 2015).

There are certain inherent shortcomings in modelling data such as variation of DON content in different regions despite having same varietal or weather setup. Since, these cannot be captured while modelling with agronomic and climatic variables, their validation over large areas is non-consistent (Franz et al. 2009).

2.5 Speptoria Blight

There are two main pathogens assocoiated with Septoria blotch disease in wheat. *Zymoseptoria tritici* (formerly known as *Mycosphaerella graminicola* or *Septoria tritici*) (*Zt*) is the causal agent of septoria tritici blotch (STB), the primary leaf disease of wheat in temperate wheat growing regions and *Septoria nodorum* (teleomorph: *Leptosphaeria nodorum*) causing septoria nodorum blotch (SNB). This disease has become a major constraint to wheat production, especially in high-rainfall areas. Under high disease pressure, the disease infects upper leaves and ear heads and causes shrivelling of kernels and deteriorates grain quality. Cool temperatures associated with frequent rains favours epidemic development in susceptible cultivars of wheat (Thomas et al. 1989). The optimum temperature for infection is 16 to 21 °C with at least 6 hours of leaf wetness. Latent period of infection for the fungus is 21 to 28 days. The spores are dispersed by rain splashes as they are trapped in sticky masses.

The fungus *Septoria tritici* survives through the summer on residues of a previous wheat crop, other grassy hosts and even wheat seed. The disease process in case of *Zymoseptoria tritici* is more complex due to its latent period and is a relatively less understood pathogen (Orton et al. 2011; Steinberg 2015). It can be as long as 14 days in spring to 28 days in cold weather. In this phase, there are no visible symptoms on plant, despite a compatible reaction between pathogen and host (Orton et al. 2011). The curative azole fungicides used in the blotch management are under constant threat due to resistance development in the pathogen. *Z.tritici* has a high gene flow rate and thus lot of sexual recombinations occur within a planting season in a field (Eriksen et al. 2001).

Alternate host in the vicinity of the crop plays a crucial role in disease development. *Z. tritici* has been reported on 26 grasses Suffer et al. (2011) and one non-graminaceous chickweed. So far, risk associated with presence of alternate hosts is not very clear (Fones and Gurr 2015).

STB cause yield losses ranging from 31% to 53% (Eyal et al. 1987; Polley and Thomas 1991). The incidence of septoria leaf blotch is on the rise for last three decades and they damage around 50 million ha of wheat around the world. STB has been reported to cause EU €280–1200 million losses per annum in Europe (Fones and Gurr 2015) and around AU$ 100 million, in Australia (Murray and Brennan

2009). The disease is fast spreading in recent years (Milgate et al. 2014). SNB has been reported from France and the Scandinavian countries, but in United Kingdom, SNB has been fully replaced by STB in the 1980s (Bearchell et al. 2005). In Mediterranean region of Tunisia, septoria leaf blotch has been responsible for decreasing yields especially in durums since last four decades (Berraies et al. 2014). Actual losses associated with STB are less clear in other growing regions.

In Nordic-Baltic region, septoria tritici blotch (*Zymoseptoria tritici*) and stagonospora nodorum blotch (*Parastagonospora nodorum*) are present with variable incidence and severity in spring as well as winter wheat. STB dominated winter wheat in Denmark, southern Sweden and Lithuania. SNB dominated spring wheat in Norway with a grain yield loss of 10–11 q/ha (Jalli et al. 2020).

Based on the importance of septoria blotch, several disease prediction models have been formulated which are based on different weather variables (Coakley et al. 1985; Shaw and Royle 1993; Gladders et al. 2001; Pietravalle et al. 2003). The blotch pathogens require free water on leaves to cause infection and frequent rains for disease spread to adjoining plants. Days with rainfall of more than 10 mm or continuous wet days (3 days with at least 1 mm rain) during early growth stages of crop are the main factors which can be used to predicting disease outbreaks (Thomas et al. 1989). Sub zero temperatures has been found to decrease the risk of STB in winter wheats. Since last three decades, decision support systems have been in use which converts complex agro meteorological information relating to disease production in a crop in an easy to understand way.

DSS has been used to reduce pesticide load using Danish system PC-Plant Protection (Secher 1991), available with Danish farmers since 1993. A web based decision support system available as crop protection online (CPO) Rydahl (2003) has been in use in Denmark since 2002. The model uses rainfall data and gives decision on spray requirement based on varietal resistance (Henriksen et al. 2000). Four rainy days with rainfall of 1 mm or more during wheat growth stage 32 in susceptible cultivars and 5 days during GS 37 in resistant cultivars will require spraying to control septoria blotch. SeptoriaSim along with humidity models were refined by Axelsen et al. (2020) which could reduce number of sprays to control septoria blight in farmers' fields along with marginal edge in yield.

Most of the septoria blotch models are weather based but rarely consider the role of crop canopy in development of epidemics. Since, the disease progression in time and space occur through rain splashed pycnidiospores, the crop architecture i.e. distance between leaves (Audsley et al. 2005), plant height (Bannon and Cooke 1998) and resulting microclimate inside the plant canopy should be a key feature of any model that predict disease progression from lower leaves to upper ones during crop growth. Robert et al. (2008) were successful in combining virtual 3D wheat architecture crop model ADEL (Evers et al. 2005) with septoria disease model (Rapilly and Jolivet. 1976) with little modification. There model describes the disease dispersal with lesion development based on spatial advance of crop canopy. The model considered dispersal unit (DU) i.e. spores splashed with rain droplets as the most important factor responsible for disease lesion production and further spore production on this diseased tissue. In ADEL crop simulation model, Phyllochron proved the major contributor followed by leaf size, stem elongation rate and the internodal length. Three year climate scenario used in this study predicted favourable, intermediate and un-favourable disease development scenario which matched the ground results of disease in Grignon, France. Therefore, this model can efficiently predict blotch disease in case crop ideotype is known.

Beest et al. (2009) in England developed an early warning prediction model to contain septoria blotch at wheat GS 31. They used Window-Pane approach (Pietravalle et al. 2003) to work out the most appropriate relationships between disease and weather at a stage where it is difficult to access the disease physically. The authors took into account the pathogen build up period that will ultimately correlate to disease when weather and crop stage are ideal. Out of three models formulated while taking into account rain and minimum temperature, rain and wind run and vapour pressure and wind run; the former gave the strongest relationship between disease and weather. The total rainfall occurring 80 days prior to GS 31 and minimum temperature above 0 °C in 50 days (Jan-Feb) and maximum temperature below 4 °C (Feb-March) starting from 120 days before GS 31 were found to give accurate disease predictions. The rain and minimum temperature model has two parts Model[e] and Model[f] as mentioned in Table 2.4.

If Model[e] is satisfied than, regression model equation Model[f] will give the epidemic prediction, where $p > 0.5$ means epidemic development. For different resistance categories of cultivars, the model was re-structured for resistant cultivar:

$$Model^c : 0.053 \times Rain^d + 0.038 \times T\,min^e - 6.80 > 0$$

Intermediate cultivar:

$$Model^c : 0.027 \times Rain^d + 0.023 \times Tmin - 3.88 > 0$$

Susceptible cultivar:

$$Model^c : 0.046 \times T\,min^e - 4.20 > 0$$

[c]is the equation of the model to predict an epidemic if the statement is true.

[d]is daily rain accumulated is more than 3 mm in an 80 day window preceding GS 31.

[e]is daily minimum temperature accumulated >0 °C in a 50-day period starting from 120 days preceding GS 31.

Two Weather based mechanistic models Model Aand Model B developed in UK predicted the germination and growth of *Z. tritici* spores on wheat leaves to predict the final disease severity. One spore materialising to one lesion was the underlying principle used for prediction. Model A could differentiate areas with different disease incidence but could not predict severity due to limitations associated with the observed disease and climate data and plant growth parameters including host resistance (Chaloner et al. 2019). There model required high resolution data for climate-derived parameters, such as temperature, rainfall and leaf wetness to predict accurately. These models could not capture high spore density situations and the following pycniospore infections.

Model B has two further limitations, firstly model B, is parameterized using an experimentally derived thermal performance curve for *Z. tritici*, but the experimental data is restricted to the range 10–22 °C. As this does not cover the entire range of conditions experienced in UK wheat-growing areas, the curve for model B had to be extrapolated. In contrast, the data used to parameterize model A was in the range of 0–30 °C and required less extrapolation. Secondly, the equation in model B did not incorporated the death of spores over time. So, all the spores landing on the leaf remains in the model until it grow and infect the leaf, thereby giving false prediction information. The authors emphasized the inclusion of pathogen biology to increase the fit of the models.

Another mechanistic model, PROCULTURE after GS32 (second node detectable), was developed in Belgium to predict the progress of Septoria leaf blotch on winter wheat in western Europe (Luxembourg). The model could accurately predicted SLB in 2000 and 2002 on susceptible and semi-susceptible varieties with a probability of detection (POD) of more than 0.90 (El Jarroudi et al. 2009). During 2001, the false alarm ratio (FAR) in the model remained high. So, actual disease based on prediction could not be validated although the POD never fell below 0.90. The model however overestimated disease periods by 50 per cent in weakly susceptible cultivars especially on leaves close to flag leaf. Under worst-case scenario or with 7 day forecasted weather data (Global Forecast System, National Centers for Environmental Prediction) the model yielded promising results for predicting disease progress and yield loss even without actual weather data. Junk et al. (2008) got a continuous spatial coverage of the country through amalgamation of PROCULTURE in offline mode to 12-hourly operational weather forecasts from an implementation of the Weather Research and Forecasting (WRF) model for Luxembourg at 1 km resolution. As the WRF model did not provide leaf wetness directly, an artificial neural network (ANN) was used to model this parameter. El Jarroudi et al. (2017b) later modified the model by including Fourier transform method (FTM) for frequency domain analysis of three intra-day meteorological variations of air temperature, humidity and rainfall from 2006 to 2009. The authors found contrasting differences in intraday meteorological variations among two sites which otherwise behaved similarly when compared at diurnal, dekadal and intra-seasonal scales. Fourier-transformed data/methods approach was found to specify the microclimate conditions prevailing at a given site which could help in improving the prediction accuracy of disease forecast models involved in regional warning systems and decision support systems.

In India, Pant et al. (2016) developed models to forecasting spot blotch severity in susceptible and resistant cultivars of wheat under irrigated timely sown (ITS), irrigated late sown (ILS) and rainfed timely sown condition (RFTS) based on maximum temperature, relative humidity and their combination. Lower RMSE value of MLR models at jointing and flowering stage was found to predict disease more accuratly than other stages. The significance of maximum spot blotch infection index (asymptote) and minimum time lag (m) has been shown to be influenced byinteraction between temperature and relative humidity (Viani et al. 2017). Their model depicted decreased dependence of relative humidity duration on spot blotch infection with increase in temperature upto 29 °C while it increases above till 34 °C (Table 2.4).

2.6 Powdery Mildew (PM)

Powdery mildew affects the wheat yield and cause significant economic loss worldwide (Sharma et al. 2004; Strange and Scott 2005). To effectively manage the disease and reduce the dose of chemicals, there is urgent need to forecast the disease in wheat fields accurately. Various prediction models based on weatherfor PM forecasting has been developedby various workers (Daamen and Jorritsma 1990; Holb and Füzi 2016). Some of the important models have been listed in Table 2.5 which indicated that there are several tools to model one or several steps of the *Blumeria graminis* f. sp. *Tritici (Bgt*) life cycle. Liu and Shao (1998) demonstrated a strong relationship of temperature, sunshine duration and rainy days the occurrence of disease, and rainfall was the mostcritical factor related to the disease epidemic. A simple approach in this regard was introduced with the disease severity threshold by Kasbohrer et al. (1988). A disease incidence threshold of 70% was identifed by Klink (1997) to avoid yield damage. A similar but more complex method based on threshold systems like PC-Plant Protection was developed by Secher et al. (1995).

A local model following the role of temperature and RH for the condial production and wind speed for the release of conidia of Powdery mildew fungus was developed.An hourly development value of the infection is computed, which adds up for every hour until an exceedance of the value “1” which indicated a successful infection. The similar method is used to calculate incubation (Friedrich 1994; Friedrich 1995a; Friedrich 1995b; Friedrich 1995c).

A decision support system baesd model MIDAS was developed by Jensen and Jensen (1996) for the management of PM in winter wheat. Temperature, humidity and wind are usedin the MIDAS model. In the subsystems, they used deterministic model which further used thermal weeks to show the temporal progression during a wheat growth period. Each thermal week derived from the sums of daily mean air temperature and it represents one timestep. The calculations both for the host’s treatment as well as pathogen development are made for every time step resulting in a disease-level where disease prediction comes close to the observation. Bruns (1996) developed the MEVA-PLUS on the basis of the model MEVA which aimed at the prognosis of the damage due to PM on winter wheat. Bruns (1996) referred to the GEMETA model of Hau (1985). The daily maximum and minimum temperature and the precipitation sum represent the weather in the MEVA-PLUS model. By using the information of monitoring intial infectionthe model run, the implemented GEMETA model and calculates a prognosis of the infestation and calculated the possible damage that can be caused due to the infection and thus developed different crop loss functions. The validation of MEVA-PLUS was done by comparing observed and predicted disease severity values at different plant growth stages. In

Table 2.5 Important models developed for the prediction of powdery mildew

Parameters/models	Specific conditions/ equations	Year	Country	References
Decision support system MIDAS	Temperature, humidity and wind	–	DenMark	Viani et al. (2017)
MEVA-PLUS	Coefficients of determination (R2) between 0.00002 and 0.796.-	–	–	Chaloner et al. (2019)
WHEat GROwth SIMulation (WHEGROSIM)	$PLA_{Lj} = PLA_{L(j-1)} + (DPLA_{Lj}) \cdot CV \cdot LL_L$ where PLALj is the infected leaf area, PLAL (j-) is the infected leaf area of the foregone timestep, DPLALj is the daily increase of infection, CV is a parameter for the wheat variety and LL_L is the leaf layer	1991–98	Italy	Viani et al. (2017)
Mechanistic simulation model WHEATPEST	Daily temperature and radiation	2008	Europe	Chaloner et al. (2019)
Precipitation, temperature, sun radiation, humidity, and two remotely sensed features including reflectance of red band (Rr)	Spatial distribution and temporal dynamics of the disease	2010–2012	China	Viani et al. (2017)
Wheat growth situation (NDVI), habitat factors (land surface temperature, LST) and meteorological conditions (rainfall and air temperature)	A decision tree was constructed to identify four infection severities (healthy, mild, moderate and severe) R2 = 0.999 with 83.33% forecasting accuracy	2010–11	Michigan, US	Chaloner et al. (2019)
Forecasting models based on meteorological factors and spore concentration	Spore concentration was the most important of all of the variables studied, including weather	2009–2012	China	Cao et al. (2015)
Moderate resolution imaging Spectroradiometer (MODIS) time-series data products	In this model, the wheat areas were identified using 8-day interval normalized difference vegetation index (NDVI) dataset at 250 m resolution	2015	China	Zhao et al. (2018)
Average temperature, average maximum temperature and positive degree days, rainfall and mean wind velocity	Accumulated spore concentration and weather variables	2015	China	Gu et al. (2020)

the start of the season, (Bruns 1996) coeffcients of determination (R2) between 0.00002 and 0.796 was achieved by using this modelwhich decreased with time.

Rossi and Giosuffe (2003) developed a model to predict PM on winter wheat using infection chain. Like the model of Friedrich (1994) this model also requires data on temperature, vapour pressure deficit, rainfall and wind. The disease progress can be predicted by using the following formula based on logistic function:

$PLALj = PLAL(j\text{-}1) + (DPLALj)\ \_\ CV\ \_\ LL_L.$

where PLALj(infected leaf area), PLAL(j-1) (infected leaf area of the foregone timestep), DPLALj = daily increase of infection, CV = parameter for the wheat variety and LL_L = leaf layer. The daily increase in disease was calculated by a submodel, based on infection chain. They used the model given by Friedrich (1994) as well as WHEat GROwth SIMulation (WHEGROSIM) (Rossi et al. 1997b). The modeal simulated the disease with a R^2 of 0.89.

The mechanistic simulation model known as WHEATPEST was developed by Willocquet et al. (2008) to know the effects of various pests and pathogens infestations on winter wheat. It needs data on daily temperature and radiation as well as drivers for production situation and for injury profiles. An injury profile was generated from the combined effects of various pests such as fungi, aphids and weeds etc. Like the model InfoCrop given by Aggarwal et al. (2006), the crop yield assessment simulation models needs the actual data on infestation events to calculate the potential crop damage. The model's outputs are the development stage of the crop, the dry biomass, the leaf area index and the expected yield.

Recently many studies are using multispectral and hyperspectral remote sensing data at the leaf or canopy levelfor the field-based identification investigation of wheat PM, (Zhang et al. 2012; Zhao et al. 2012; Cao et al. 2015).

The meteorological and phenological data are used to predict the disease most of the studies. But the prediction accuracy and timeliness have usually been affected due to lack ofsufficient number of weather stations, especially for a large-scale region. The satellite remote sensing technology can help in this regard to quickly acquire wide field and time series images (Dutta et al. 2008).It can facilitate the monitoring and forecasting of the plant diseases over the inefficient, labour-intensive and time-consuming traditional methods. (Nilsson 1995; Franke and Menz 2007; Huang et al. 2007; Bock et al. 2010; Huang et al. 2012). Zhang et al. (2014) integrated meteorological and remote sensing data with crop characters and habitat traits for predicting PM. They constructed a disease-forecasting model using four meteorological factors (precipitation, temperature, radiation and humidity) and remote sensing data [reflectance of red band (Rr) and land surface temperature (LST)] to predict dynamics of the disease over space and time. This integrated model gave a accuracy ranging from 69% to 78% for disease forecasting. Similarly, Zhang et al. (2014) used 9 different remotely sensed variables to developthe powdery mildew forecasting model and Ma et al. (2016) used L and sat 8 remote sensing image and meteorological data to develop themodel for predicting PM at filling stage.

So it can be interpreted that thereis a great potential for predicting the PM occurrence probability by combining the meteorological and remote sensing data.

Zhao et al. (2018) predicted the disease by using the Moderate Resolution Imaging Spectroradiometer (MODIS) time-series data. The wheat areas were identified using 8-day interval Normalized Difference Vegetation Index (NDVI) dataset at 250 m resolution. A decision tree wasconstructed to identify four infection severities (healthy, mild, moderate and severe) using three kinds of forecasting factors (wheat growth situation), habitat factors (LST) and meteorological factors (rainfall and temperature). The coefficient of determination (R^2) was 0.999 between the remote sensing based and the statistical data and the overall forecasting accuracy was 83.33%.

Apart from all these, some of the forcastiong studies in PM occurance are based on the dispersal and deposition of conidia, which are further affected by meteorological factors (Granke et al. 2014). Significant correlations was observed t between spore concentration and many weather factors (Troutt and Levetin 2001; Burch and Levetin 2002), which are useful in predicting the number of conidia in the air (Bruno et al. 2007). Pakpour et al. (2015) reported a negative correlation between the conidia concentration in the air and rainfall. Cao et al. (2012) monitored air borne conidia of Bgt and analyzed relationships between airborne inoculum with weather variables and disease index. A forecasting model was developed by them in the year 2015 (Cao et al. 2015). They monitored the spore concentrations in air using spore samplers and RT PCR. TA positive correlation was found between the temperature, solar radiation and rainfall with conidial concentrations and hence disease development. Although there was a negative correlation between relative humidity and spore concentration, but it was positively related with disease development. Stepwise regression models were obtained for predicting the dynamics of airborne conidia based on the PDD and accumulation of rainfall ($R^2 = 0.31$, $P < 0.01$), the positive degree days ($R^2 = 0.16$, $P = 0.04$) and mean temperatures ($R^2 = 0.24$, $P = 0.01$) at three locations, respectively (Cao et al. 2015).

Recently Gu et al. (2020) also showed that accumulated spore concentration and 10-day temperature variables (average temperature, maximum temperature and PDD) aongwith rainfall and mean wind velocity. In this model they reported that conidial concentration and weather factors are playing equal rolefor predicting the development of PM. Disease development is highly influenced by the prevailing microclimate. and hence a crucial factor for disease prediction. It is well known that the regional conditions significantly influence the disease severity (Junk et al. 2016). Therefore, monitoring the dynamics of airborne conidia and meteorological variables are of help to predict the disease and give recommendations for the management of disease.

There have been reports about the negative effect of solar radiation on the development of PM (Liu and Shao1998; Zahavi et al. 2001; Austin and Wilcox 2012).

2.7 Wheat Blast

Wheat blast is known to be caused by the *Triticum* pathotype of *Magnaporthe oryzae* (MoT). It was first reported in 1985 in Paraná State of Brazil (Igarashi et al. 1986) and further moved into other areas of Brazil and South America fom where erratic epidemics have been reported (Urashima et al. 2004; Kohli et al. 2011, Cruz and Valent 2017). Most recently, it has been appreared in Bangladesh demonstrating the threat of global spread via the movement of infected seed or grain. The fungal pathogen affects wheat earheads, with symptoms closely resembling FHB. Wheat blast can cause yield losees as high as 64% and may lead to total crop failure (Goulart et al. 2007). Fungicides arenot effective under very severe conditionsbut canmanage the disease when disease levels are low tomoderate. Till date no effective source of durable resistance have been found (Cruz and Valent 2017). So disease management requires identification of new resistance sources and a complete understanding of pathogen ecology and disease epidemiology.

As wheat blast is an emerging disease of wheat, hence not many epidemiological studies have been conducted. There are several studies establishing that blast severity varies greatly with weather conditions, cultivar, and plant organ infected (Goulart et al. 2007; Urashima et al. 2009). Countinous rainy and warm weather is necessary for pathogen survival during spring and summer seasons. The production of conidia of M. grisea is known to be favored by the combination of high relative humidity ($\geq$90%) and temperature around 28 °C (Alves and Fernandes 2006).High temperatures coupled with excessive rain, long and frequent leaf wetness, and poor fungicide efficacy are the major factors favouring the occurrence ofdisease in severe form (Goulart et al. 2007). Environmental conditions thatfavour the disease development are similar for MoT, MoO and MoL strains (Anderson et al. 1947; Uddin et al. 2003; Cardoso et al. 2008).

P. oryzae grow better at 21–27 °C and 10–14 h of spike wetness (Ou 1972) hence the temperature and spike wetness are the most important environmental factors affecting the disease development in different hosts.

Cardoso et al. (2008) predicted wheat blast the intensity based on the temperatures and the durations of wheat spike wetness under artificial epiphytitic conditions using standard methods. The study indicated that temperature (25 and 30 °C) with spike wetness (25 and 40 h alone)can favor wheat blast intensity. T The wetting-period data fitted the Gompertz model, and combining the temperature and wetting-period equations as.

Z = 0.00108*(T-10.0)**1.8)*((35.0-T)**0.762)*(0.847/(1 + EXP (6.498–0.348*HW),

The interaction between the leaf wettness and the average temperatureforms the bases of many disease forecasting systems (Zadoks and Schein 1979). The effect of the interactions between temperature and the durationof the wetting-period on infection occurring under our controlled conditions can cause distortions when applied to the field and theaccurate prediction under field conditions is difficult Sutton. 1988). To partially overcome such issue divide the data on the response to infection (daily probability of infection; DPI) values Following the procedure of those models developed by Krause and Massie (1975) and Madden et al. (1978) predicted the disease using a climatic model to develop a table of critical periods containing four arbitrary selected categories of infection efficiency, denominated daily severity values (DSV). A computer program was developed to automatically combine mean temperature values and wetting-period values collected in the field byweather stations and calculates both daily probability of infection (DPI) values and the sum of the DPI (DDPI) values over a specific period. The main limitation of infection-based models as that of Cardaso et al. (2008) lies in the assuming the prescence of abundant inoculum during the susceptible period. However, in temperate regions freezing temperatures affect the inoculum production (Farman et al. 2017). Contrastingly, under tropical climatic conditions, inoculums production is limited more by moisture than temperature. So, a model that can predict both inoculum potential (IP) and favorability for infection would have a wider application for predicting wheat blast.

Fernandes et al. (2017) developed a prediction model by using the historical data analysis of epidemics and weather series in Brazil for the period of 10 years. A specific database management application (agroDb) helped to visualize and identify patterns in weather variables during two major outbreaks (2004 and 2009). An IP and a spore cloud (SPOR) variable were estimated to predict inoculum build-up and availability. A day favoring infection (DFI) was conditioned to rules relating temperature and relative humidity for the day derived from the epidemic analysis. Successful daily infection (INF) during a DFI was conditioned to IP $>$ 30 and SPOR $>$ 0.4. The model was tested at heading date for 10 planting dates, spaced 5 days apart, within a year, totaling 320 simulations. The model described well epidemic and non-epidemics conditions for the historical dataset, and was able to correctly predict.. The CSM-CROPSIM model included in DSSAT 4.6 (Decision Support System for Agrotechnology Transfer) was used to simulate growth and development of spring wheat (cultivar BRS Louro). The model was coded in R statistical and programming lan-guage (**R** CoreTeam2017) and uses Shiny (Chang et al. 2017) for visualizing model outputs (http://gpca.passofundo.ifsul.edu.br/agroweb). The model starts by the time of emergenceof the first cohort of heads, which is predic ted by the wheatmodel. Three variables are predicted: IP and SPOR are continuous variables and DFI is binary (0, 1).

In the erratic diseases like wheat blast model development and validation is complicated due to the lack of detailed field disease data. Some models have been developed by using the data under controlled conditions. Further refinements and evaluations will require long-term field data. Concludingly high humidity and warm temperatures are more relevant for predicting observed wheat blast out-breaks.

2.8 Conclusions

To prevent the losses in ecofriendly manner in the absence of host plant resistance, the limited and timely application of fungicides as guided by the disease forecasting models plays an important role. Incase of wheat various disease forecasting models have been developed globally by following different methods and using different weather variables alongwith crop growth stages to predict the disease over space and time. EPIPRE, RUSTDEP, EPIWHEAT, DONCAST, and WHEATPEST etc. are a few. Most of these models are focused on one disease or two and moreover they are designed with regional specificity. So there is a dire need to develop a kind of forecasting system by using the recent advances in information technology or by adopting multi-desiplinary approach, which can deal with multiple diseases of a wheat and should be applicable globally. Based on these prediction models decision support system should be developed for our ultimate beneficiaries i.e. farmers by guiding them when and where to apply the fungicides for successful management of the wheat diseases.

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Leaf Blight Disease of Wheat and Barley: Past, Present and Future

3

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3.1 Introduction

Foliar wheat blight is also referred to as Spot blotch or *Helminthosporium* leaf blight in South Asia. The causative agent *B. Sorokiniana* is a globally distributed hemi-biotrophic fungus. Spot blotch is one of the production restrictions for wheat crops grown in warm, humid tropics (Singh et al. 2015; Gupta et al. 2018b). The disease is known as one of the major biotic problems in the warm-humid tropics of India, Bangladesh, Nepal, Brazil, Bolivia, Argentina and Paraguay (Gurung et al. 2013; Singh et al. 2015; Navathe et al. 2020a; Wu et al. 2020). In a favourable climate, the disease spreads rapidly after anthesis, destroying the plant's photosynthetic ability during the grain filling affecting grain yield and quality (Joshi et al. 2007a; Singh et al. 2018). The disease is exacerbated by occasional rain under warm temperatures requiring extra measures to control losses. It has been demonstrated that spot blotch resistance is under polygenic regulation (Joshi et al. 2004; Kumar et al. 2009, 2010, 2016b; Singh et al. 2018; Tomar et al. 2020; Roy et al. 2021). Resistant cultivars display fewer and smaller lesions than those that are susceptible. It was found that the reproduction of spores in these lesions was delayed and decreased in volume (Eisa et al. 2013; Poudel et al. 2019). This non-specific pathogen infects several graminaceous hosts and a wide variety of other plants also. It affects wheat and barley among cereals and creates significant damage. The spot blotch is prevalent in South Asia, primarily in the East Gangetic Plains, on ten million hectares of wheat crop (Singh et al. 2015). The disease is responsible for substantial losses in yield

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ranging from 15.5% to 19.6% per year (Dubin and Ginkel 1991) and probably up to 100% during the epidemic year (Singh et al. 2015). Globally, spot blotch is influenced by an estimated 25 mha of wheat, representing about 12% of the total area (Duveiller et al. 2005). Due to favourable weather, such as warm air temperature, >12 h of leaf wetness and plant age, spot blotch tends to flare up (particularly after ear emergence; Zadok's GS 55) (Chaurasia et al. 1999; Joshi et al. 2007c). Besides, the early establishment of the pathogen has favoured a growing number of cloudy and foggy days from November to February (Duveiller et al. 2005; Joshi et al. 2007c). *B. Sorokiniana* is considered a relatively weak parasite, and its success depends mainly on weakened host plants that respond to various environmental stresses such as high temperatures (Rosyara et al. 2007, 2008), nutrient deficiency (Regmi et al. 2002) and water stress (Sharma and Duveiller 2006). These multiple stresses decrease plant fitness which makes *B. sorokiniana* more invasive and promotes spot blotch. Because of climate change, nutritional and water deficiency issues, the spot blotch is predicted to become more severe in the future (Sharma and Duveiller 2006).

Breeding attempts have resulted in many improved spot blotch-resistant wheat genotypes (Singh et al. 2015). Delivering new genotypes to farmers with a strong resistance level and high yield will provide a cost-effective and environmentally sustainable solution to spot blotch (Singh et al. 2015).

3.2 Leaf Blight Pathogen "*Bipolaris Sorokiniana*": Taxonomy and Nomenclature

In wheat, barley, maize and other small grain cereals, *Bipolaris sorokiniana* (Sacc.) shoemaker is an important fungal pathogen causing many diseases known as spot blotch (S.B.), common root rot (CRR) and leaf spot. The generic name *Bipolaris* was first used in 1959 for species of *Helminthosporium*, with fusoid conidia displaying bipolar germination; the genus was typified by species *B. maydis* (Manamgoda et al. 2012). Recently, a recommendation for the retention of the term *Bipolaris* in contrast to the term *Cochliobolus* (Rossman et al. 2013) was also made and endorsed by online voting organized by the International Fungal Taxonomy Committee. Most *Bipolaris*/*Cochliobolus* species were differentiated based on conidia and conidiophores' morphology (Sivanesan 1987). Less notable was the form and colour of ascospores teleomorphs within the genus *Cochliobolus* (typified by *C. heterostrophus* and *C. sativus*). The *C. sativus* is the teleomorph of the sexual form of anamorph *B. sorokiniana* which received further support from several studies where molecular data were used. The analysis of ribosomal Deoxyribonucleic acid (DNA) polymorphism [e.g. 28S rRNA, 5.8S rRNA and internal transcribed spacers (ITS1 and ITS2)] and other protein-coding barcoding genes (e.g. GAPDH coding genes and elongation factor 1α) backed the hypothesis that the anamorph *B. sorokiniana* and *C. sativus* represent two stages of the same species (Manamgoda et al. 2012, 2014).

Bipolaris sorokiniana has many synonyms, including *Helminthosporium sativum*, *H. sorokinianum*, *Drechslera sorokiniana* and teleomorph *C. sativus*

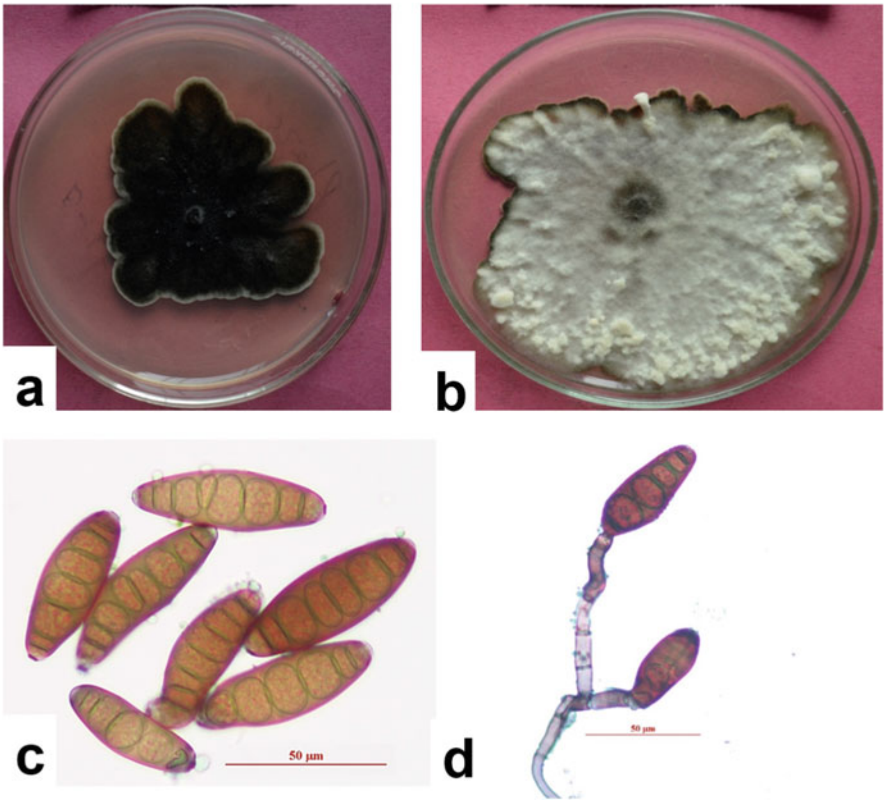

Fig. 3.1 (**a**–**b**) Typical black, dark brown to greyish white colony of *B. sorokiniana* on potato dextrose agar medium. (**c**) Typical olive brown, oblong in form, and with 3–9-thick-walled septate, tapered conidia. (**d**) Monosporic conidiophores carrying single conidium

(Manamgoda et al. 2012). Different *Bipolaris* species, including *B. sorokiniana,* are distinguished based on conidia and conidiophore morphology. A key had been prepared for this reason with a description of all species of *Bipolaris* (Manamgoda et al. 2014). The conidia (15–20 μm × 60–120 μm) born on conidiophores (100–-150 μm × 6–8 μm long) emerge on the leaf surface in the air. Each conidiophore may carry either a single conidium (monosporic) or multiple conidia (polysporic). These conidia are olive brown in colour, oblong in form and with 3–9 μm thick-walled septate, tapered with a conspicuous basal scar towards the edge (Fig. 3.1). Generally, during the cropping season, many conidial cycles are produced and spread into the air causing secondary infections (Duveiller et al. 2005; Gupta et al. 2018a).

3.3 Molecular Markers for Pathogen Diagnostics and Genomic Resources Available

Molecular techniques have revolutionized the study of the genetic variation among plant pathogens, and, in particular, the polymerase chain reaction (PCR) technique provided the foundation work to understand taxonomy and population structure. The flow of genes and other evolutionary forces can lead to the spread of single gene or DNA sequences and even establish entire populations in various regions. The multinucleated state of mycelial cells and conidia of *B. sorokiniana*, with subsequent heterokaryosis that could lead to mitotic recombination and new haploidization arrangements, may account for the DNA polymorphism observed for this pathogen (Aggarwal et al. 2010, 2011). A diagnostic PCR assay was successfully developed to detect *B. sorokiniana* in leaves and roots of barley and wheat (Matusinsky et al. 2010). The assay was based on the *Brn1* locus involved in the melanin biosynthesis pathway of *B. sorokiniana.* A quick and reliable diagnostic marker based on PCR ($SCRABS_{600}$) was developed to detect the pathogen at the pre-symptomatic stage in the soil and wheat leaves (Aggarwal et al. 2011; Jaiswal et al. 2007) reported the 20 primers of random amplified polymorphic DNA (RAPD) to observe the heterogeneity between diverse established groups *B. sorokiniana* population. Aggarwal et al. (2009, 2010) proposed the Universal Rice Primer (URP)-PCR approach for studying molecular heterogeneity among 40 virulent isolates of *B. sorokiniana* collected from different Indian regions. Out of 12 URP markers used in the study, ten markers effectively produced polymorphic fingerprint patterns. The study recommended one of the 12 markers, URP-2F (5’GTGTGCGATCAGTTGCTGGG 3′), which could be used as specific markers for the identification of *B. sorokiniana*.

Further, a PCR-amplified band of 650 bp obtained in *B. sorokiniana* isolates using universal rice primer (URP 1F) was cloned in pGEMT easy vector and sequenced. Based on sequences, six primers were designed, out of which a primer pair RABSF1 (GGTCCGAGACAACCAACAA) and RABSR2 (AAAGAAAGCGGTCGACGTAA) amplified a sequence of 600 bp in *B. sorokiniana* isolates, which could clearly distinguish *B. sorokiniana* from other fungal plant pathogens (Aggarwal et al. 2011). Recently, an immunological assay based on antibodies against *B. sorokiniana* was implemented in combination with 18S rDNA sequencing to detect the fungal pathogen in infected wheat leaves (Chakraborty et al. 2016). A detailed account of diagnostic assays and marker systems used for genetic variation in foliar blight pathogens is presented in Table 3.1.

The isolate reflecting virulence diversity is a vital resource for breeding wheat varieties with genetic resistance. A global set of germplasm may help tackle the spread of virulent pathotypes to new regions by growing resistant germplasm to particular pathotypes from all parts of the world. Determination of accurate chromosome number ($n = 15$) by the flow cytometry and molecular karyotyping and chromosome structural variations studied (Valjavec-Gratian and Steffenson 1997; Zhong and Steffenson 2001). Estimating the genome’s size (*35 Mb) complete sequencing (Condon et al. 2013, 2014; McDonald et al. 2018) has now become

Table 3.1 Molecular diagnostics and genetic variability studies in *B. sorokiniana* and related species causing foliar blight in crops

Pathogen	Host	Markers/ Assay	Application	Reference
B. sorokiniana	Wheat	SCAR	Diagnostic PCR	Aggarwal et al. (2011)
B. sorokiniana	Wheat	COSA_F/R	Diagnostic PCR	Matusinsky et al. (2010)
B. sorokiniana	Wheat	18S rDNA, ELISA	Detection	Chakraborty et al. (2016)
B. sorokiniana	Wheat	URP-PCR	Genetic variability	Mann et al. (2014)
B. sorokiniana	Wheat	URP-PCR	Genetic variability	Aggarwal et al. (2010)
B. sorokiniana	Wheat	RAPD	Genetic variability	Aggarwal et al. (2009), Müller et al. (2005), Jaiswal et al. (2007)
B. sorokiniana	Wheat	ITS (PCR-RFLP), RAPD	Genetic variability	Oliveira et al. (2002)
B. sorokiniana	Wheat, barley	AFLP	Genetic variability	Zhong et al. (2002)
B. sorokiniana, B. oryzae, B. spicifera B. victoriae	Switchgrass	SSR	Genetic variability	Fajolu et al. (2013)
B. sorokiniana	Barley	RAPD	Genetic variability	Baturo-Ciesniewska (2011)
A. tritici	Wheat	ITS	Species identification	Mercado Vergnes et al. (2006)
B. sorokiniana, Curvularia spicifera and *Curvularia inaequalis*	Wheat	ITS, GPDH, ISSR, iPBS	Species identification	Özer et al. (2020)

accessible. Molecular maps of the whole *C. sativus* genome (anamorph *B. sorokiniana*) were successfully developed based on molecular markers [e.g. restriction fragment length polymorphisms (RFLP), amplified fragment length polymorphism (AFLP), simple-sequence repeats (SSR)] covering all 15 chromosomes (Mann et al. 2014). For this project, a segregating population derived from crossing two distinct isolates [ND90Pr (virulent) 9 ND93–1 (non-virulent)] was used. Some AFLP markers have been converted into sequence characterized amplified region (SCAR) markers, and probes have been established for each chromosome and virulence. Various genomic resources available in the public domain are listed in Table 3.2.

Table 3.2 Database progress of *B. sorokiniana*—a foliar blight/spot blot pathogen

Source		Description	**Total**
Literature	Books and reports, MeSH, ontology used for PubMed indexing, NLM collections		675
Genes	PopSet	Sequence sets from phylogenetic and population studies	80
	Gene	Collected information about gene loci	12,418
	EST	Expressed sequence tag sequences	–
	GEO databases and profiles	Functional genomics studies, gene expression profiles	30
	HomoloGene and UniGene	Homologous gene sets for selected organisms, clusters of expressed transcripts	–
Proteins	Identical protein groups	Protein sequences groups by identity	18,902
	Protein	Protein sequences (translation elongation factor 1α (4), β-tubulin (17), glyceraldehyde-3-phosphate dehydrogenase (7), scytalone dehydratase (1), RNA-binding protein-BRN1 (12)**,** manganese superoxide dismutase (1))	35,627
	Conserved domains, protein clusters, sparkle and structures	Conserved protein domains, sequence similarity-based protein clusters, functional categorization of proteins by domain architecture and experimentally determined biomolecular structures	–
Genomes	BioProject	Biological projects providing data to NCBI	35
	BioSample	Descriptions of biological source materials	75
	Nucleotide	DNA and RNA sequences	13,856
	SRA	High-throughput sequence reads	81
	Assembly, bio-collections, clone, genome, GSS and probe	Genome assembly information, museum, herbaria and other biorepository collections, genomic and cDNA clones, genome sequencing projects by an organism, genome survey sequences and sequence-based probes and primers	07
Genetics	Genetics	Genotype/phenotype interaction studies, genome structural variation studies, genetic testing registry, medical genetics literature and links, short genetic variations	–
Chemicals	PubChem bioassay	Medicinal chemistry, drug discovery, pharmaceutical genomics and informatics research, small-molecule and RNAi screening data along with associated annotation information	09
	BioSystem, PubChem compound and PubChem substance	Molecular pathways with links to genes, proteins and chemicals; chemical information with structures, information and links; and deposited substance and chemical information	–

Data from NCBI (https://www.ncbi.nlm.nih.gov/labs/gquery/all/?term=Exserohilum+rostratum&utm_source=Datasets) and EMBL database (www.embl.org) accessed February 2021

3.4 Host Range and Pathogenic Variability

Bipolaris sorokiniana can live in a variety of environments. It may also infect durum wheat (*T. durum*), dicoccum wheat (*T. dicoccum*), barley (*Hordeum vulgare*), triticale, rye (*Secale cereale*), maize (*Zea mays*), pearl millet (*Pennisetum typhoides*), foxtail millet (*Setaria italica*), tufted airplant (Guzmania species) and Panicum (Manamgoda et al. 2012; Singh et al. 2016b). *B. sorokiniana* was found to be capable of infecting 29 crop species, including some grasses, in a study conducted in northeast China (Acharya et al. 2011).

Morphological, pathological and molecular approaches were used to identify and investigate the heterogeneity among *B. sorokiniana* isolates (Ghazvini and Tekauz 2007; Jaiswal et al. 2007; Oliveira et al. 1998, 2002; Poloni et al. 2009; Zhong and Steffenson 2001; Mahto et al. 2012; Gurung et al. 2013; Sultana et al. 2018). Pakistan, Nepal, India, Bangladesh, Mexico and the United States have all recorded variations in pathogenicity levels of the same pathotype under different conditions/ locations (Mahto et al. 2012; Asad et al. 2009).

From 127 *B. sorokiniana* isolates collected from barley in Canada (Ghazvini and Tekauz 2007) identified eight virulence groups using 12 differential lines. In another analysis, Arabi and Jawhar (2004) discovered that the virulence of B. sorokiniana from Syrian barley was highly variable across barley lines with varying levels of resistance. An Australian study identified 11 pathotypes among 31 B. sorokiniana isolates collected from barley and wheat using 12 differential barley lines (Knight et al. 2010). Mahto et al. (2012) tested the aggressiveness of eight *B. sorokiniana* isolates on eight wheat cultivars at the seedling stage. He discovered that fungal isolates and wheat cultivars interact differently. Gurung et al. (2013) tested 96 *B. sorokiniana* isolates on 12 separate wheat lines. Based on phenotypic data analysis, he reported that his isolates were divided into 47 pathotypes. In areas where wheat is continuously grown, a specific pathotype can be more virulent.

Virulence can also be influenced by hyphal fusion, nuclear migration or the emergence of a multinuclear state (Chand et al. 2003; Pandey et al. 2008). CHEF electrophoresis was used to examine the karyotypes of 16 isolates obtained from barley grown in various parts of the world (Brazil, Canada, Japan, Poland, Uruguay and the United States), representing all three pathotypes (0, 1, 2) (Zhong and Steffenson 2007). Unless large-scale structural changes were involved in differentiation, 14 of the 16 isolates (except North Dakota isolates ND90Pr and ND91-Bowman) each displayed a distinct banding pattern, which is surprising.

The causes of genetic variation between isolates are majorly related to mutation, migration/gene flow and recombination within the *B. sorokiniana* population could all be factors. In the pathogen's population, recombination may occur between isolates with high virulence levels (Zhong and Steffenson 2001).

3.5 Disease Cycle and Epidemiology of the Disease

The pathogen has a biotrophic period confined to individual epidermal cells and a necrotrophic phase of growth involving host cell apoptosis as a hemi-biotroph (Kumar et al. 2002; Aggarwal et al. 2008). At the same time, *Cochliobolus sativus* is regarded as a sexual condition that is uncommon and does not serve as a source of inoculum or infection (Fig. 3.2). Following the germination of the host seed, the pathogen emerges and rapidly reaches the plumule and then the coleoptile tip (Reis and Forcelini 1993).

The pathogen's subsequent development and growth causes accelerated damage to the leaves and spikes, resulting in yield loss (Chand et al. 2010). When an infection is airborne, the conidia germinate and form germ tubes on the leaf surface (Acharya et al. 2011). Within 8 h, appressoria appears, followed by infecting hyphae (Jansson and Akesson 2003), which invade the cells and multiply in the leaf's mesophyll tissue (Acharya et al. 2011). Direct penetration has also been confirmed (Eisa et al. 2013). Favourable weather conditions, such as warm air temperature, >12 h of leaf wetness and plant age (especially after ear emergence, ZGS 55), cause spot blotch to flare up (Chaurasia et al. 1999; Joshi et al. 2007c).

Besides, from November to February, a growing number of cloudy and foggy days favoured the pathogen's early establishment (Duveiller et al. 2005; Joshi et al. 2007c). *B. sorokiniana* is a relatively weak parasite, and its effectiveness is dependent mainly on compromised host plants reacting to various environmental stresses

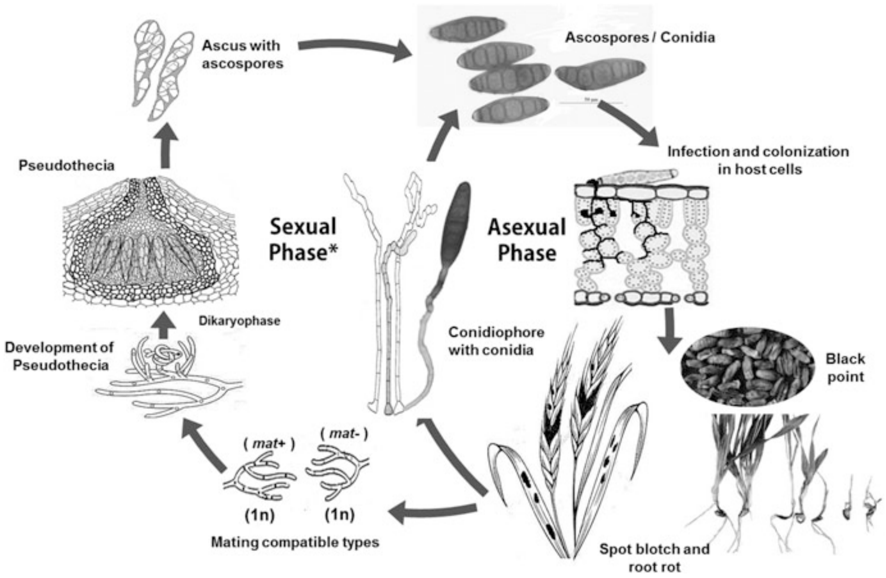

Fig. 3.2 Life cycle of the foliar blight pathogen *B. sorokiniana.* *Sexual phase is rarely observed in the nature. Asexual phase repeats multiple times. Fungus can survive on seed, numerous alternate weed hosts, soil and stubble to cause infection during the next cropping season

such as high temperature (Rosyara et al. 2007, 2008), nutrient deficiency (Regmi et al. 2002) and water stress (Rosyara et al. 2007, 2008; Sharma and Duveiller 2006). Multiple stresses minimize plant fitness, causing *B. sorokiniana* to become more invasive and promote spot blotch. Due to the rising problems of climate change, nutritional and water shortage, the spot blotch is expected to worsen in the future (Sharma and Duveiller 2006; Gupta et al. 2018a). Spot blotch causes photosynthesis loss, premature leaf senescence, reduced grain filling, low kernel weight and extreme grain yield reductions combined with terminal heat stress. The disease is expected to become a more severe constraint for wheat production if the forecast that air temperature will rise in the coming decades is accurate (Gupta et al. 2018a).

3.6 Resistance and Susceptibility Genes for Leaf Blight Disease

3.6.1 Virulence Pattern and Genes Associated with the Pathogen

There is no physiological specialization or physiological race supported by the observed heterogeneity in pathogenicity between the strains (Duveiller and Sharma 2009). Isolates can be distinguished by virulence- and aggressiveness-dependent pathotypes (Table 3.3; Valjavec-Gratian and Steffenson 1997; Knight et al. 2010). Previously, three pathotypes (0, 1 and 2) of *B. sorokiniana* were identified in three differential barley lines (ND 5883, Bowman and ND B112) based on their virulence patterns in North Dakota, USA (Valjavec-Gratian and Steffenson 1997). A few other highly virulent pathotypes on barley have recently been reported in Canada, North Dakota and Morocco (Gyawali et al. 2018; Leng et al. 2016).

The recurrent progression in the disease's mean severity from less virulent strains of different origins to more virulent strains indicates differences in quantitative aggression. The widespread occurrence of aggressive pathogen strains is capable of overcoming promising resistance sources under experimental conditions. This leads to the potential rapid adaptation of strains when releasing resistant cultivars (Maraite et al. 2006; Sultana et al. 2018). The development of more severe symptoms in adult plants tends to be caused by low-molecular-weight pathotoxins such as prehelminthosporol, helminthosporol, helminthosporic acid, sorokinianin, bipolaroxin and bipolenin K-J (Carlson et al. 1991; Nakajima et al. 1998; Vergnes et al. 2006; Jahani et al. 2014; Phan et al. 2019).

Genetic analysis of one of the most virulent isolates, ND90Pr, showed that a single locus (VHv1) is responsible for its virulence (Valjavec-Gratian and Steffenson 1997; Zhong et al. 2002). Besides, genome sequencing and functional analysis identified two genes that are essentially needed for the virulence of ND90Pr isolate encoded for non-ribosomal peptide synthetases (NRPSs) (Condon et al. 2013). The finding also suggested that the ND90Pr virulence factor is possibly a selective toxin (HST) metabolite of the secondary host. Further research on CsLaeA, CsVeA, CsVelB, CsVelc and CsVosA (Velvet Complex Global Regulators) has also shown that secondary metabolite variably played a significant role in virulence

Table 3.3 Details of phytotoxins and virulence factor so far reported to be involved in the pathogenicity of *B. sorokiniana*

Host	Phytotoxin/pathogenicity factor	Chemical nature	Reference
Wheat, barley and monocot grasses	Prehelminthosporol	Sesquiterpenoid metabolite	Carlson et al. (1991), Nilsson et al. (1993), Åkesson and Jansson (1996), Apoga et al. (2002)
Wheat, barley and monocot grasses	Prehelminthosporolactone	Sesquiterpenoid metabolite	Carlson et al. (1991)
Wheat, barley and monocot grasses	Helminthosporol	Sesquiterpenoid metabolite	Carlson et al. (1991)
Wheat, barley and monocot grasses	Helminthosporol victoxinine	Sesquiterpenoid metabolite	Carlson et al. (1991)
Wheat, barley and monocot grasses	Sorokinianin		Nakajima et al. (1998)
Wheat, barley and monocot grasses	11- epiterpestacin	Sesterterpene	Nihashi et al. (2002)
Wheat, barley and monocot grasses	Bipolaroxin	Eremophilane sesquiterpene	Jahani et al. (2014)
Wheat	Bipolenins K–N	Sativene-type sesquiterpene	Phan et al. (2019)
Barley	VHv1	Effector protein	Condon et al. (2013)
Wheat and barley	LaeA, VeA, VelB, VelC and VosA	Lae and velvet proteins	Wang et al. (2016)
Wheat	ToxA	Necrotrophic effector protein	McDonald et al. (2018), Faris and Friesen (2020), Navathe et al. (2020a, 2020b), Wu et al. (2020)

(Wang et al. 2015, 2016). Very recently Zhang et al. (2021) identified novel effector CsSp1 essential for the colonization of *B. sorokiniana* in wheat. CsSp1 is putative secreted protein with N-terminal single peptide induced and localized in nucleus and cytoplasm of plant cell during early infection.

3.6.2 Necrotrophic Effector-Triggered Susceptibility in Wheat and Barley

Interestingly, necrotrophic pathogens required dead plant tissue to survive and trigger cell death responses in the host plants in different ways. This provides a source of nutrients to the pathogen and resulting in a compatible response. This relationship represents the paradigm of "gene-for-gene at the molecular level", but the result changes from tolerance to susceptibility due to phytopathogens' lifestyle.

Besides, interactions of "gene-for-gene" are generally qualitative, but interactions of "inverse gene-for-gene" in necrotrophic pathosystems often have an additive or quantitative effect. The host susceptibility factor characterization demonstrates homologous domains as identified by Faris et al. (2010). The sensitive gene (*Tsn1*) of the necrotrophic effector (*ToxA*) in wheat has all resistance characteristics, that is, S/TPK and NBS-LRR domains (Faris et al. 2010). Necrotrophic effectors have evolved to manipulate the plant immune system to benefit the pathogen, generally seen as tiny, secreted proteins with high cysteine content. Four economically significant wheat and barley necrotrophic plant pathogens (*Pyrenophora tritici-repentis, Parastagonospora nodorum, Pyrenophora teres* and *B. sorokiniana*) follow "inverse gene-for-gene" interaction to cause disease. The diversifying selection may then be placed on the host receptor in the hypothetical case of a necrotrophic pathogen interacting with the host receptor, trying to eradicate the recognition. Typical interactions occur in the inverse gene-for-gene model, as shown by the interaction between *Tsn1* and *ToxA*. Recently, this interaction was identified in wheat-*B. sorokiniana* pathosystem from Australia, the United States and India (McDonald et al. 2018; Friesen et al. 2018; Navathe et al. 2020a). It has been shown that *Tsn1* and ToxA do not interact directly, but for the induction of host defence responses and the translocation of ToxA into a cell, *Tsn1* is explicitly required (Faris et al. 2010). Tsn1 may function as a "guard" for the ToxA target. *Tsn1* may recognize the target protein's alteration and initiate cell signalling pathways upon modifying the target effector (Friesen et al. 2008).

Necrotrophic specialists commonly select multiple effectors that target unique loci with a wide range of pathogen populations via the host genome (Friesen et al. 2008). This has opened up a unique opportunity for genetic resistance in breeding programmes by selecting against functional susceptibility factors. Several host loci are necessary for this situation to eliminate all the effectors and achieve "resistance successfully." Successful breeding to tackle necrotrophic specialists like *B. sorokiniana* requires knowledge of the regional diversity of pathogen isolates and the host susceptibility target.

3.7 Screening of Genotypes for the Disease Resistance

3.7.1 Methods

Most of the studies performed under-regulated growth conditions do not mimic the region's natural agro-climatic conditions. The resistance mechanism found at the early seedling stage does not correlate with the adult plant stage's resistance mechanisms. Therefore, spot blotch resistance breeding and screening must be performed under field in a disease conducive environment. In many locations in South Asia, field screening for spot blotch resistance is based on natural infection at mega-environment 4 (ME4) and mega environment ME5A (ME5A) mega-environment hotspots, such as the lowland (Terai) region of Nepal, eastern Uttar Pradesh (India) or western Bengal (Joshi et al. 2007b). Jessore (Bangladesh), Encarnación (Paraguay), El Batan (Mexico) and North Dakota (USA) are other potential sites for successful genotype screening. In vitro, the pathogen can be maintained in jars on sterilized sorghum grains. The selection pressure can be increased by spreading these infested grains at various developmental stages, such as ear initiation or physiological Zadoks 45–55 (Zadoks et al. 1974; Chand et al. 2010). Additional humidity can be created by giving intermittent irrigation at 4 days to establish the artificial epiphytotic conditions.

The disease severity score is accurate based on the percentage of the diseased leaf area. The field resistance assessment is based on a visual assessment of the upward disease progression from the lower canopy level since the spot blotch is either seed or soil-transmitted. As a modification of Saari and Prescott's severity scale, the double-digit scale (00–99) developed (Saari and Prescott 1975; Eyal et al. 1987) is the most efficient and widely adopted. The vertical progression of the disease is indicated by the first digit (D1) of this scale. The second digit (D2) indicates the severity of the disease based on the total leaf area. The disease score can be converted to disease severity (D.S.) in percentage terms using the following formula (Eyal et al. 1987; Duveiller et al. 1998):

$$\%\mathrm{Severity} = (\mathrm{D1}/9) \times (\mathrm{D2}/9) \times 100$$

Repeated observations are needed as the spot blotch progresses rapidly after anthesis, so disease scores must be reported between the anthesis and the dough stage after inoculation at 3–7-day intervals over a 3–4 week period. The area under the disease progression curve depicts the disease's progression, which is commonly used to measure resistance. The area under disease progress curve (AUDPC) can be calculated by using the formula given by Shaner and Finney (1977) and Madden et al. (2007):

$$\mathrm{AUDPC} = \sum\nolimits_{i=0}^{n-1} [\ \{(Yi + Y(i+1))/2\} \times (t\ (i+1) - ti)]$$

where Y_i = % disease severity level at time t_i, $t_{(i\ +\ 1)}$—t_i = time (days) between two disease scores and n = number of dates at which spot blotch was recorded.

The spot blotch screening relies more on multi-location nurseries (Singh et al. 2015). A large spectrum of resistance/tolerance in the breeding pool has been acquired by the notion of shuttle breeding and multi-location screening undertaken by the various wheat and barley breeding programmes (Singh et al. 2015). The most promising spot blotch-resistant lines established through various national and international breeding programmes are special nurseries such as CIMMYT-CSISA-SB, Helminthosporium leaf blight screening nursery, IIWBR—plant pathological screening nursery and leaf blight screening nursery. Therefore, multi-year/multi-site screening is justified in identifying genotypes that are responsive across environments. These nurseries use various assessment systems to classify the stable resistance that may be used in the breeding programme or may even be released directly as the varieties.

3.7.2 Symptom Types

Spot blotch resistance in wheat cannot be defined solely based on lesion characteristics. For aggressiveness and symptom forms, a series of *B. sorokiniana* strains were analysed using wheat genotypes with different resistances and continuous variation (Chand et al. 2003; Pandey et al. 2008). Some strains have induced small lesions in the most susceptible genotypes, while others have induced symptoms even in the most resistant ones (Chand et al. 2010; Navathe et al. 2020a). In one country or even in one area, more and less aggressive strains may be isolated simultaneously.

Thus, there is no specific pathogenic pattern of *B. sorokiniana* strains and consists of a spectrum of varying aggressive strains (Maraite et al. 2006; Duveiller and Altamirano 2000). Molecular and pathogenicity studies also confirm this (Poloni et al. 2009; Chand et al. 2003; Mahto et al. 2012; Sultana et al. 2018). *B. sorokiniana* majorly causes spot blotch on leaves, root rot and rare seedling blight. Symptoms also appear on the sheath, the node and the glume (Chand et al. 2010; Bashyal et al. 2011a, b). Small, dark brown, 1–2 mm in diameter, with no chlorotic margin, are characterized as early leaf lesions (Fig. 3.3). These lesions quickly spread to several centimetres in susceptible genotypes to form oval to elongated light to dark brown blotches that coalesce and result in necrosis of the leaf tissue (Chand et al. 2010). Under humid conditions, abundant development of conidia can be observed in old lesions. The chlorotic margin is often seen as diffusing from the lesion’s border due to the phytotoxin or necrotrophic effector (*BsToxA*) produced by the pathogen (Navathe et al. 2020a). CRR is typically found in cooler dry environments and characterized by brown spotting on the inner crown and internodes. In the field, asexual anamorphic stage *B. sorokiniana* is found to be associated with root or leaf lesions. Generally, the disease begins with older leaves and gradually progresses upward (Chand et al. 2010).

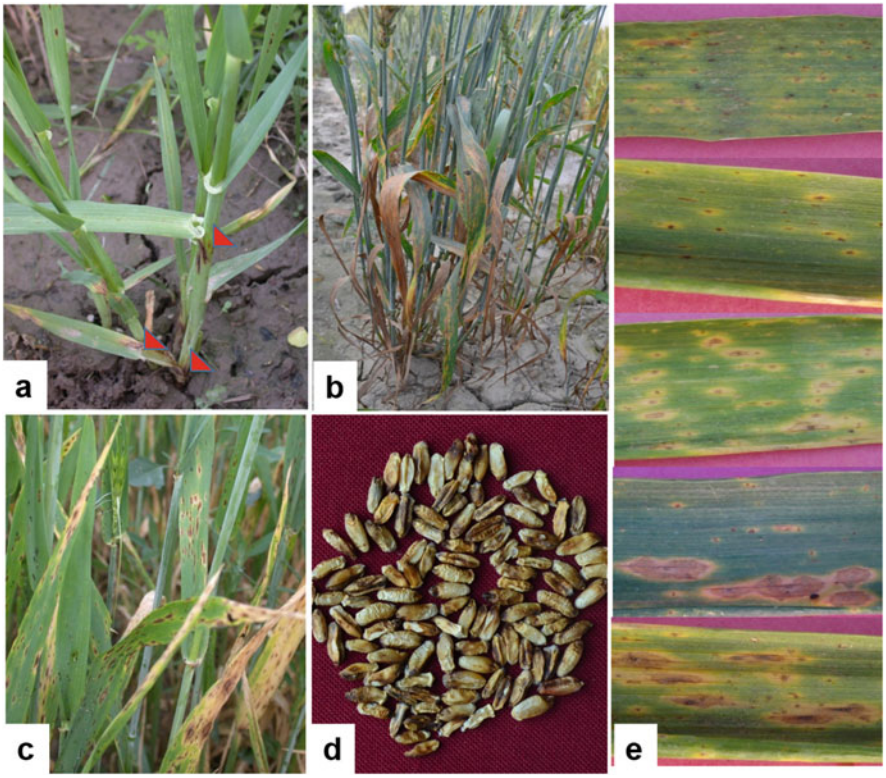

Fig. 3.3 Typical symptoms of foliar blight (spot blotch) (**a**) on the coleoptile of the seedlings, (**b**) on wheat at post-anthesis stage, (**c**) on barley at booting stage, (**d**) shriveled grains of wheat with black point symptoms, (**e**) various types of symptoms on wheat leaves indicating necrotic spots, spots with yellow halo, colleased and elongated spots at later stages of infections

3.8 Breeding Efforts for Foliar Blight Resistance in Wheat and Barley

3.8.1 Wheat

Based on comprehensive analyses over several years, many genotypes with spot blotch resistance are now available for the breeding programme. Good resistance sources, such as Ning 8201, Chirya 3, Yangmei 6, HD4502, Saar, BH1146, Chirya 1 and Tksn1081/*A. squarrosa*, Mayoor are being used in the spot blotch research (Table 3.4). Cultivars with a relatively high degree of resistance in the Indian national wheat programme have been produced and made available to farmers. Molecular markers have been commonly used to identify loci and interval mapping for quantitative disease resistance based on linkages involving the use of mapping

Table 3.4 Various spot blotch resistance sources reported in wheat and barley

Origin	Names of genotypes	References
Wheat		
Afghanistan	Pamir 94, Katia-1,OK82282//BOW/NKT/3/F4105, RENESANSA, VORONA/CUPE	Bainsla et al. (2020)
Bangladesh	BAW 969, BAW 1006, BAW 1008	Sharma and Duveiller (2006), Siddique et al. (2006)
Brazil	BH 1146, CEP 14, CNT 1, Ocepar 7, Trigo BR 8	Mehta (1998), Sharma et al. (2004b), Sharma and Duveiller (2007), Caierão et al. (2014)
China	Chuanmai 18, Fang 60, G162, Jinmai 4058, Longmai 10, Longmai 10,370, Ning 8201, Ning 8319, Ning 9415 Quangfeng, Shanghai #4, Shanghai #158, Suzhoe #1–58, Suzhoe #8, Suzhoe #128-OY, Yangmai 6	Sharma et al. (1997, 2004a, b, c), van Ginkel and Rajaram (1998), Joshi et al. (2004, 2007a, b); Ibeagha et al. (2005), Sharma and Duveiller (2006), Kumar et al. (2009, 2010), Bainsla et al. (2020)
CIMMYT	Attila = NL781 = PBW343, BOW 'S', M3, Chirya 1, Chirya 3, Chirya 7, Chukui#1, Cigm 90.455, FFN/VEE#5, HLB25, Kauz/Vee/Muna, Milan/Shanghai #7, SM-4-HSN24, Vayi#1, ALTAR84/AE.SQ//2[a]SERI/3/CHIR3, PSN/BOW//ROEK/3/MILAN, Mayoor, Tksn1081/Ae. squarrosa(222) and CNDO/R143//ENTE/MEXI.2/3/AE.SQUARROSA (TAUS)/4/WEAVER	Chaurasia et al. (1999), Sharma et al. (2004a, b, c), Ragiba et al. (2004), Duveiller et al. (2005), Ibeagha et al. (2005), Joshi et al. (2007a, b, c), Neupane et al. (2007), Sharma and Duveiller (2006), Kumar et al. (2009, 2010fs), Zhu et al. (2014), Singh et al. (2015)
India	ACC 8226, BW 14999, CPAN 3003, CPAN 3048, CPAN 4006, CPAN 4007, CPAN 4011, CPAN 4042, CPAN 4065, CPAN 4070, HD 2662, HD 2819, HP 1729, HP 1808, HUW234, HUW206, HUW289, HUW302, HUW305, HUW323, HUW325, HW 2093, K9107, M3109, PBW 343, PBW 486, RAJ 3702, Triveni, WH542, YS116 (Yangmai 6/Sonalika), 56 accessions in NBPGR	Chaurasia et al. (1999), Joshi and Chand (2002), Joshi et al. (2004), Sharma et al. (2004a, b, c), Sharma and Duveiller (2006), Khan and Chowdhury (2011), Kumar et al. (2015, 2016a, b), Singh et al. (2016a, b)
Nepal	Achyut, Bhrikuti, BL1693, BL1724, BL1740, BL1813, BL1883, BL2069, BL2127, BL3704, BL4148, Gautam, Mayoor, NL835, NL868, NL872, WK 1204	Sharma et al. (2004a), Sharma and Duveiller (2006), Joshi et al. (2007b), Mahto et al. (2011)
Pakistan	Abadgar 93, Anmal 91, Auqab 2000, Bahawalpur 2000, Bahkhar 2002, Bakhtawar 92, Darawar 97, Faisalabad 85, Inqilab 91, Iqbal 2000, Kaghan 93, Kirin 95, Kohistan 97, Kohsar 95, Magalla 99, Mexi Pak, Moomal 2002, Nowshera 96, Parwaz 94, Pasban 90, Pirsabak 2005,	Iftikhar et al. (2012)

(continued)

Table 3.4 (continued)

Origin	Names of genotypes	References
	Punjab 96, Saleem 2000, Sariab 92, SH 2002, Shafaq 2006, Shaheen 94, Shahkar 95, Soughat 90, Wafaq 01, Watan 94	
Barley		
USA	Minn 33, Minn 65–241, Minn 65–243, Minn 65–244, Minn 7	
India	NDB 1173, DL88, BHS 380, PL 807, DWR49, VJM-360, VJM-389, VJM-507, VJM-515, VJM522, KARAN-757, KARAN-1057, HBL 233,VLB 35, DWRB 180,	Verma et al. (2013), Jain et al. (2014)
Nepal	BB86019-1 K-3 K-0 K3, ACC#2087, ACC#2496, ACC#2476, ACC#2030, B86152–2-2-0 K,ACC#GHv06816, ACC#1612, ACC#1597, ACC#2087, ACC#2441, ICB-105969-3-2-0 K, ACC#2079, XVEoLA-2,886,019-1 K-3 K-0 K3, ACC 2087, ACC 2441, ACC GHv-06816, ACC 1597, ACC 1612, ACC 2059, ACC 2032	Subedi et al. (2020)

[a]Updated after Gupta et al. (2018a, b).

populations. More than 70 QTLs and a series of genome-wide association studies have been published (Gupta et al. 2018a).

Only four resistance genes of spot blotch (*Sb1, Sb2 Sb3* and *Sb4*) have been mapped to date (Lillemo et al. 2013; Kumar et al. 2016b; Lu et al. 2016; Zhang et al. 2020). *Sb1* was mapped on 7DS, co-located with the locus of leaf rust resistance, *Lr34*, with pleiotropic effects on stripe rust (*Yr18*), stem rust (*Sr57*), powdery mildew (*Pm38*) and leaf tip necrosis (*Ltn1*) (Lillemo et al. 2013). In the 0.62-cM genetic region, *Sb2* was delimited to 5BL between the markers *Xgwm639* and *Xgwm1043* (Kumar et al. 2015). Within a 0.15-cM genetic interval spanning a 602-kb physical genomic area of Chinese Spring chromosome 3BS, the third gene, *Sb3*, was mapped (Lu et al. 2016). *Sb4* was recently mapped using bulked RNA-Seq (BSR-Seq) technology at a 1.19-cM genetic interval corresponding to a 1.34-Mb physical genomic region chromosome 4BL (Zhang et al. 2020).

Additionally, relative expression analysis in response to Indian virulent isolate (BS-112) showed that eight defence-related genes, namely, chitinase, glucanase, PR-1, lipid transfer protein, serine palmitoyl-transferase, UDP-glycosyl transferase and translationally controlled tumour protein, and DNA J-like, were highly expressed in resistant genotype (Chirya 7) (Gurjar et al. 2018).

3.8.2 Barley

Great efforts have been made over the last few years to identify and map QTLs and genes for spot blotch tolerance in barley germplasms (Bilgic et al. 2005, 2006; Bovill et al. 2010; Grewal et al. 2012; Castro et al. 2012; Zhou and Steffenson 2013; Berger et al. 2013; Wang et al. 2017, 2019; Novakazi et al. 2020). Among these, the most studied were *Rcs5* and *Rcs6*. *Rcs5* was originally mapped for resistance to pathotype 1 (isolate ND85F) on the short arm of chromosome 7H using a double-haploid (D.H.) barley obtained from the cross of the cv. Steptoe and Morex (Steffenson et al. 1996). Furthermore, the fine mapping revealed that the gene was located in the ~240 kb region of the 7H chromosome in the genotype Morex (Drader 2011). Another gene, *Rcs6,* was mapped to the short arm of chromosome 1H for resistance pathotype 2 (isolate ND90Pr) using the D.H. population from a cross of Calicuchima-sib/Bowman-BC (Bilgic et al. 2006). Fine mapping delimited *Rcs6* and its counterpart susceptibility allele *Scs6* at a genomic interval of 125 kb at 1H Morex at the same locus (Leng et al. 2018). At the *Rcs6* locus in Bowman, fine mapping of the susceptibility allele (*Scs6*) confined the gene to the *Mla* complex locus on chromosome 1H (Leng et al. 2018).

Both *Rcs5* and *Rcs6* are recessive alleles, and the corresponding dominant alleles are the functional ones responsible for susceptibility (Ameen et al. 2016; Leng et al. 2016). Eleven Mendelian loci (*Rcs1–Rcs6, Rbs7*, two unidentified genes and two loci associated with *gsh2* and *vrs3*) for spot blotch resistance in barley have been identified (Bilgic et al. 2006). *Rcs1, Rcs2, Rcs3, Rcs5, Rcs6* and *Rbs7* were reported for chromosomes 2(2H), 5(1H), 7(5H), 1(7H), 5(1H) and 6H, respectively.

3.9 Management of the Leaf Blight Disease

3.9.1 Chemical and Biological Controls of Leaf Blight Disease

For disease suppression of early seedling infection, fungicide seed dressings or fungicides applied in-furrow with fertilizer may help. The choice of fungicide should be determined based on the target diseases. Applying foliar fungicides to the crop is to delay the development of the disease and preserve the green leaf area. It decreases the effect of diseases on yield and grain quality. The cost-effectiveness of foliar fungicide applications depends on the nature of the disease, the varietal resistance, the crop's yield capacity, the outlook for grain quality and the growing environment.

Seed treatment with Carboxin (Vitavax @ 2.5–3 g/kg seed protects the crop) can effectively control the initial inoculums under a high black point incidence. Results showed that treatment of seeds with Vitavax power @ 3 g/kg of seed followed by two sprays of propiconazole @ 0.1% at the time of initiation of the disease on flag-1 leaves and the soft dough stage was best to reduce the severity of the disease. Seed treatment, either with triadimenol or carboxin + thiram combined with a single post-flowering foliar spray of fungicides, has been recommended to minimize grain yield loss (Sharma-Poudyal et al. 2016). Additionally, Bayleton, propiconazole and tebuconazole (at 0.1%) are broad-spectrum fungicides selective against foliar diseases like powdery mildew, spot blotch and net blotch (Singh et al. 2016a; Gangwar et al. 2018). In another study, Pradeep and Kalappanwar (2016) suggested three sprays of pyraclostrobin 13.3% + epoxiconazole 5% @ 0.1% at an interval of 15 days from the date of appearance of typical symptoms, which was an effective fungicide with a maximum reduction of disease severity (88.27%) and black pointed grain. This combination can be used as an alternate fungicide to triazoles, especially Propiconazole or Tebuconazole. Application of foliar fungicides Azoxystrobin 125 g a.i./ha at Zadok's growth state ZGS 50 and ZGS 60 is good protection against spot blotch. It also maintains the chlorophyll content, higher vegetative index (NDVI), reduced canopy temperature and higher yield. This maintained cell redox balance also (Navathe et al. 2020b). The use of proven antagonists of soil and seed-borne plant pathogens for biological control of spot blotch is a new way to manage the disease. Mandal et al. (1999) screened 16 species of fungi for their antagonistic behaviour on *B. sorokiniana* (in his research, called *Drechslera sorokiniana*). The effect of mycelia and culture filtrates of bioagents on germination of conidia and mycelial growth of *B. sorokiniana* was examined for this reason. The culture filtrates were also used for spraying already inoculated wheat seedlings (3- to 4-leaf stage) with a conidial suspension of *B. sorokiniana*. Sixteen species, including *Trichoderma reesei*, *Trichoderma pseudokoningii, Trichoderma hamatum, Talaromyces flavus, Chaetomium globosum* and *Trichothecium roseum*, had an inhibitory effect on conidial germination and mycelial growth. The spot blotch lesions on wheat leaves were significantly decreased by three of these species (*T. reesei, T. pseudokoningii, C. globosum*). In another study (Aggarwal et al. 2004), *Chaetomium globosum* was also efficient in biological control, so this is one of the most compelling antagonists used for biological control. However, this needs validation with multi-location trials under AICRP to release a formal recommendation for the farmers' use.

3.9.2 Integrated Disease Management

Fungicidal foliar sprays and seed treatment will effectively control the disease. Ecofriendly methods, such as botanical, agronomic and lower fungicide usage, can control foliar blight. To understand the constraints faced by small farmers, realistic approaches to controlling foliar blight of wheat in South Asia must consider the sustainability of the entire rice–wheat system. It is critical to prioritize resource-saving technologies that enable farmers to sow wheat earlier in the season to avoid post-anthesis heat stress and yield reductions. Early wheat sowing can be aided by a variety of techniques, including zero tillage, reduced tillage with a happy seeder and surface seeding—a conventional practice discovered by farmers in marginal areas of eastern Uttar Pradesh (Joshi et al. 2007a, b, c), the impact of which on leaf blight epidemics is least known. Zero tillage shortens the time it takes to sow wheat by 5 to 15 days, resulting in 10 to 25% yield over traditional methods.

Long-term trials in the Indo-Gangetic Plains revealed that potash plays an essential role in reducing leaf blight infection levels. Potassium helps the canopy remain green for longer. Potassium deficiency exists in many parts of South Asia, but most farmers do not use this nutrient for various socioeconomic reasons. When 40 kg of K2O was added to deficient soil, the AUDPC decreased by 50%. Similarly, when farmyard manure (FYM) (10 t/ha) is applied, the AUDPC decreases by 30%, implying that not only FYM contains a large amount of potassium but also high levels of organic matter are advantageous and minimize disease severity (Duveiller 2004). In a warm wheat-growing environment, yield loss due to disease could be minimized by growing the selected cultivars with a balanced fertilizer dose of 100:50:50 N:P: K kg ha-1 (Kandel and Mahato 2009; Chaurasia and Duveiller 2006).

Among the various botanicals, Malik et al. (2008) found that using a 10% leaf extract of Rauvolfia serpentine significantly inhibited spore germination (93%). Extracts of Polygonum hydropiper, garlic (*Allium sativum*), ginger (*Zingiber officinale*) and neem (*Azadirachta indica*) were found to be effective against seed-borne infections of *B. sorokiniana* by Rahman et al. (1999). The pathogen's mycelial development was substantially hindered by both the plant extracts and the biofungicide. For further confirmation and release as formal recommendations to farmers, these results must be validated in multi-location experiments.

3.10 Challenges in Breeding for Resistance to Spot Blotch

B. sorokiniana, when forming a complex with other pathogens, such as *Alternaria triticina*, *Alternaria alternata* and *Cladosporium* spp., causes around 19% loss in yield in South Asia (Joshi et al. 2007a, b, c; Saari 1998). However, under severe disease conditions, losses may rise to 100% (Srivastava et al. 1971). The pathogen infects the leaves, roots and stem of wheat, causing spot blotch symptoms on leaves, seedling blight, kernel blight and CRR. The losses are yield penalty and grain quality deterioration, mainly due to shrivelled grains and black point development near the embryo. Despite extensive efforts, field results showed that spot blotch continues to cause substantial grain yield reductions and underscore the need for further research.

About 4000 Indian wheat lines were evaluated for their performance against blight, causing pathogens considering foliar blight's significance. However, none of the lines was found consistently resistant against leaf blight and spot blotch diseases (Goel et al. 1999). Several elite cultivars possess low to moderate levels of resistance against spot blotch. Moreover, the advanced entries in the coordinated national trials also show low resistance against the disease (Proceedings of AICW&B workers meet 2013). This highlighted the immediate need to identify and utilize new genetic stocks and genes for resistance against the disease. In a recent investigation, about 4925 wheat accessions conserved in the Indian National Genebank have been evaluated for spot blotch resistance at Cooch Behar, a hotspot for the disease (Kumar et al. 2016a). It was observed that 18.7% accessions of *T. aestivum*, 12.6% of *T. durum* and 37.5% of *T. dicoccum* exhibited resistance

(R + MR) to spot blotch. These genotypes could identify new genes for resistance to spot blotch to diversify the current gene pool that comprises merely four genes characterized for resistance to the disease.

3.11 Future Prospective

In any case, disease resistance may help reduce the likelihood of high yield losses. There is little information on the variety of isolates, pathotypes, phytotoxins, necrotrophic effectors and the different hidden mechanisms that function together to cause susceptibility to the host. The efficient identification of potential susceptible loci from breeding materials and the effective implementation of resistance will be possible by recognizing the potential molecular interactions between pathogen isolates and adapted germplasm. A resistant, high-yield cultivar is essential to empower farmers with practical, low-cost cultivation.

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Smut and Bunt Diseases of Wheat: Biology, Identification, and Management

4

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4.1 Introduction

Presently, hexaploid wheat (*Triticum aestivum* L. AABBDD) is one of the major cereal crops cultivated throughout the globe (Simón et al. 2021). It covers more than 215 million hectares (equivalent to the area of Greenland) and also holds 30.3% of land occupied by total cereals (Turgay et al. 2020). In terms of production, China, Russia, India, and the United States are top wheat-producing countries and are expected to override the rice for the most important crop. Globally, more than $50 billion worth of wheat is marketed annually and expectedly continued to enhance by 2% annually as per need of exponentially growing population and imposed food demand (Kashyap et al. 2020).

According to Food and agricultural organization assessments, biotic stresses in cereals have affected annually loss of 23 million tons, which is enough to feed 150 million people (Miraglia et al. 2009). The particular pathogen that infects the wheat crop depends upon inoculum specificity, cultivars, climate, and agronomical practices confined within the region (Singh et al. 2020a, b). The disease outbreak is confined to the regions with more significant production where the favorable conditions for crops and pathogens are present. This can be supported by the fact that Karnal bunt, a highly destructive disease, created an epidemic in one of the major wheat-growing India areas, that is, Karnal, Haryana (N 29° 41′ 8.4948“, E 76° 59’ 25.7388”) in the year of 1931.

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Despite these, the growth stages, domination of abiotic stresses, and unpredictable climate conditions are key regulators in the expression of every disease (Kumar et al. 2019). It is estimated that smut fungi are the second largest group of plant pathogenic fungi after rusts, with approximately 1450 species in about 77 genera (Gautam et al. 2021). Many of them are recognized as quarantine pathogens that adapt to the condition of new habitat via changing their race specificity (Bishnoi et al. 2020). In the smut category, flag smut incited by *Urocystis agropyri* is considered a major threat for wheat crops and restricted through import-export barriers (Kashyap et al. 2011, 2020). In India, more than 5% yield loss is caused due to *U. agropyri* through significant impact on 1000 grain weight, plant height, effective tiller number, and ear head length. It is well known that classification and identification of spore traits (size, shape, color, orientation) are tedious and need accuracy in research (Chalkley 2020).

Hill bunt is caused by *Tilletia tritici* syn. *T. caries* and *T. laevis* syn. *T. foetida,* which are confined throughout the autumn-planted and spring-planted wheat, worldwide. It is distributed mainly in Asia, Australia, North and South America, and Europe (Turgay et al. 2020). Another wheat pathogenic fungi known as dwarf bunt is caused by *Tilletia controversa* (Kuhn.) syn. *T. calospora* (Pass), and it is evident that after early spring growth, diseased plants show a defected high number of tillers. The sori formed after heading stage except for the formation of kernels. These sori of dwarf bunt exhibit rounded in shape and provide the spike a ragged appearance. The infection in covers slightly covered the small portion of individual spikes. The infected plants appear to be slightly shorter than healthy plants, and the diseased spikelet appears to flare out and take on green-greasy color. It commonly occurs on autumn-planted wheat and various genera of winter annual grasses. In the case of loose smut, *Ustilago nuda* f. sp. *tritici* affects wheat caryopsis during the flowering stage and infected seeds as primary inoculum. The pathogen flourishes within a seed and grows its mycelium toward apical portions and seed primordia. The entire inflorescence is replaced by the spores except for rachis (Dumalasova and Bartos 2016).

Mostly, smuts and bunts commonly attack reproductive parts and develop spores, sori, or smuts that infect anthers, ovules, and ovaries (Mathre 2000). In some cases, flag smut sori develop in vegetative parts (leaves and stems). The infection of smuts takes place in either embryo in which penetration usually takes place through hyphal growth on seed embryo. These infection bodies cross the testa of seed or by scutellum regions into the embryo and cause intracellular infection (Ram and Singh 2004; Toor et al. 2013; Toor et al. 2013; Kashyap et al. 2020). Furthermore, *U. agropyri* and *Tilletia controversa*, two important bunt diseases, have been observed to establish their infection using seedling mode (Kashyap et al. 2017). The leaves are completely damaged due to pathogenic attacks, and plants are unable to do photosynthesis properly that ultimately hamper their ability to complete their reproductive phase. Furthermore, the importance of these two diseases can be supported by the fact that the keywords “Smut in wheat” and “Bunt in wheat” fetched nearly 470 and 938 publications, respectively, in the Google scholar (https://scholar.google.co.in/) by March 31, 2021. The present chapter summarized the information on different types of smut and bunt, spore characteristics, management strategies, molecular diagnostics, and genetic variability.

4.2 Smut and Bunt

In the case of loose smut, the percentage of infection causes yield loss insignificant amount, for example, 1–2% of infection can decrease 5–10% profit of farmers (Abrahim 2019), whereas, in flag smut, nearly 20% of crop losses reported from Egypt, Italy, Iran, and the United States. Additionally, in the Chinese region, 90–94% of infection was observed due to devastating pathogen, *U. agropyri*. Productivity and sustainability in agriculture can be attained by enhancing crop production with the practice of high-yielding varieties or by reducing crop failure from diseases and pests (Kashyap et al. 2017). The high-yielding varieties are more susceptible to single or multiple diseases. Hence, healthy seeds or planting materials are the basic requirements for good healthy crops (Pandey et al. 2016; Wilson and Daane 2017). Seeds are known for the carrier of several disease-causing microbes (Shukla et al. 2018).

The smuts contain intercalary perfect spores having numerous sporidial structures and facultative nature. They rarely undergo basidiocarp formation, passive discharge, and completely lack polymorphism, sex organs, and heteroecism nature. In the case of bunt, the enormous number of bunt balls with a black, greasy foul smell like spores (Shukla et al. 2018). It infects flag leaves that result in induction of stunted growth and appears grey-green ink-like substance on inflorescence and seeds (Agarwal 2017; Bishnoi et al. 2020; Abrahim 2019). The spores producing fungal thread continuing in the cluster of elongated cells producing infected coleoptile instead of first leave emergence. The smut diseases are mostly internally seedborne except loose smut of wheat. The bunt diseases are chiefly externally seedborne, and fungus replaces the seed's internal machinery with a bulk of stinking ball spores. The pathogen flourishes within the plant, eventually forming smutted leaves or heads along with bunts balls spread apart more than on healthy inflorescence. Yield losses from bunt diseases are minimal but greatly impact quality traits such as color and odor (Zhao et al. 2019).

The management of smut and bunt can be achieved by cultural or escapes (changes in sowing time, field selection, disease resistance genotypes, healthy planation material, seed treatment, soil sanitation, crop rotation, eradication of secondary host), chemical methods (organic sulfur compound; inorganic sulfur compound, benzene compound, systematic fungicides, a heterocyclic nitrogen compound, organophosphate fungicide, organomercurials), biological (biological inoculum), and integrated strategies (seed certifications, crop inspections, and quarantine regulations) (Singh and Pandey 2012; Shakoor et al. 2014; Vajpayee et al. 2015; Agarwal 2017; Abrahim 2019; Hyde et al. 2019; Bishnoi et al. 2020). The detailed information on biology of smut and bunt is summarized in Fig. 4.1.

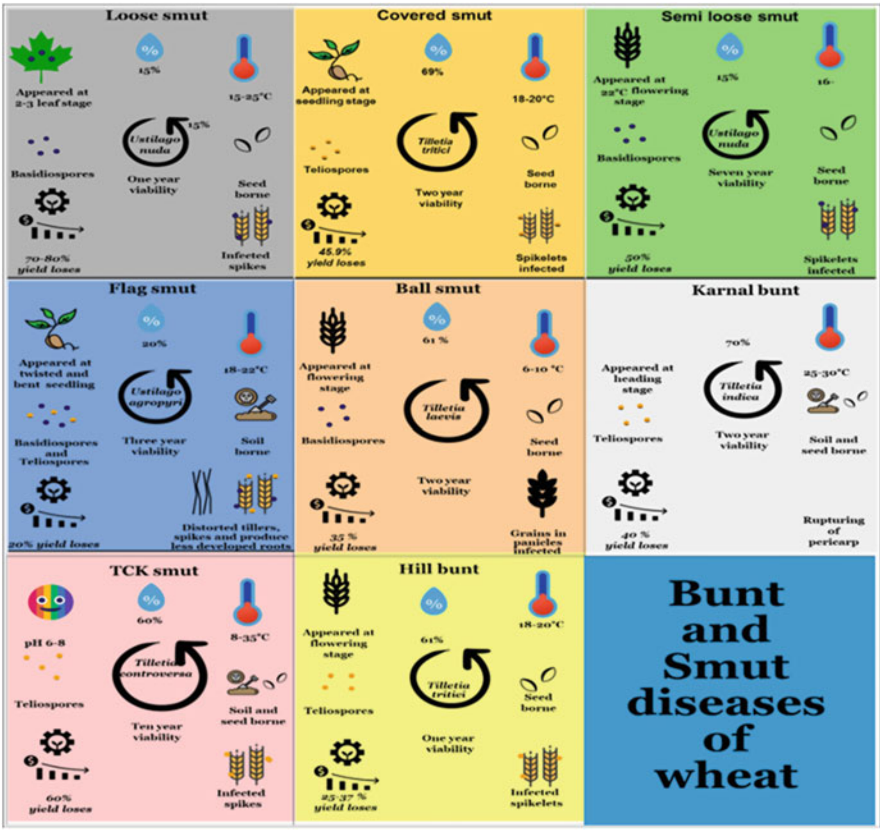

Fig. 4.1 Overview on biology of smut and bunt diseases in wheat

4.3 Wheat Bunt

The *Tilletia* genus is a cereal disease fungus spreading either systemically or locally (Pascoe et al. 2005; Carris et al. 2006). This bunt takes place in form of teliospores present in the ovaries of the plant and gives the appearance of blackened or termed as burned. The most frequent infection mode is infected seed and fungi infection wheat from the seedling stage (Turgay et al. 2020). Three genera associated with bunt diseases in wheat are *T. laevis, T. controversa, and T. tritici* (Pascoe et al. 2005). The covered smut or stinking smut is known as a common bunt that infects both winter and spring wheat. Its infection is much identical to two fungi, namely, *T. laevis* (*T. foetida and T. foetons*) and *T. caries* (*T. tritici*). These fungal pathogenic spores show variation in their wall structure such as reticulated (*T. tritici*), hyaline gelatinous (*T. controversa*), and smooth surface (*T. laevis*). These pathogens survive in soil or on seed surfaces (Pascoe et al. 2005; Turgay et al. 2020). In autumn-sowing wheat, another dwarf bunt caused by *T. controversa* has been reported. It shows a similar life cycle and disease symptoms to *T. tritici* but having variation in teliospores structure (Turgay et al. 2020). Another critical smut fungus is known as new bunt/*carie de* Karnal/Karnal bunt, or partial bunt of wheat (Table 4.1).

4.3.1 Karnal Bunt/Partial Bunt

The disease was first reported by a very famous pathologist, Mitra, in 1931 from Karnal, India (Kumar et al. 2020), so popular in terms of Karnal bunt. The pathogen target floret or ovaries that changes seeds into black powdery mass composed of thick-walled teliospores (Mamluk 1998; Kumar et al. 2020; Zhao et al. 2019). These spores are 35–50 (μm) having subglobose to globose shape, opaque black, dark reddish brown or orange in color; spores truncate, finely cerebriform/echinulate densely maybe smother or curved in appearance. Three *Tilletia* species, namely, *T. walkari* (spore size 30–45 μm; color: radish brown or pale yellow to dark, shape: globose; cerebriform, coarse, spines or irregular gaps), *T. ehrharta* (spore size 24–28 μm; subglobose to globose; opaque or dark olivaceous brown; slightly rounded to broadly truncate ate apex, rarely cerebriform, cylindrical to almost tapered spines), and *T. horrida* (spore size: 24–36 μm; light or dark chestnut brown; echinulate or cerebriform ridges) having identical morphology but different spore traits (Kochanova et al. 2004; Fang and Ramasamy 2015; Bishnoi et al. 2020). However, *T. bouteloua* (infect *Bouteloua gracilis*), *T. inolens* (on *Lachnagrostis* filiformis), *T. barclayana* (infect *Paspalum* and *Panicum*), *T. rugispora* (on *Paspalum*), and *T. eragrostidis* (on *Eragrostis*) have identical morphological features with *T. indica* (Table 4.2).

Except for Karnal, pathogens of *T. indica* or *Neovossia indica* now reported in Gujrat, West Bengal, Madhya Pradesh, Jammu & Kashmir, Punjab, Uttar Pradesh, Himachal Pradesh, Delhi, Rajasthan, and even in Iran, Iraq, Pakistan, the United States, and Sonora in Mexico (Figueroa et al. 2018; Zhao et al. 2019). Majorly, *T. indica* infects *T. aestivum* but also exhibits effect on several grass species such as *Triticum dicoccon, Lolium* spp., *Oloptum miliaceum, Bromus* spp., *Secale cereale,* and *Aegilops geniculata.* Teliospores of *T. indica* are categorized into three types based on their morphology in their life cycle (Kumar et al. 2020; Zhao et al. 2019). The non-pathogenic haploid phase grows like unicellular yeast or sporadic form. The macro/filiform conidia are primary sporidia and splash dispersed germinates to turn into an infective entity (allantoid) and reproductive (filiform) secondary sporidia. Second, the fusion of two compatible haploid cells known as filamentous dikaryon colonizes and infects tissue. Filiform sporidia enhance the inoculum through soil and plant surface but only allantoid sporidia cause infection (Kumar et al. 2020). The diseases are also known as seed-borne and airborne but did not directly pass from infected grains. These teliospores' germination depends upon temperature ranges from 15–25 °C, high moisture content, and cloudy weather after light rain cause rapid infection rate (Kumar et al. 2020; Turgay et al. 2020). During infection, primary sporidia initiate mycelium germination followed by generation of secondary

Table 4.1 Origin, causal organism, secondary host, and environmental factors that favor smut and bunt diseases in wheat

Disease	Types of smut	Causal organism	Origin of disease	Secondary host	Selected resistant variety	Environmental factors				References
						Viability in soil (year)	Temperature (°C)	pH	Humidity requirement (%)	
Smut	Covered smut	*Tilletia tritici*	Ethiopia	Wheat, barley, oat	DDK 1029	2	18–20	7	69	Borgen and Davanlou (2001)
	TCK smut	*Tilletia controversa*	Mexico	Wheat	Sonop (TD-14)	10	8–35	6–8	60	Kochanova et al. (2004)
	Loose smut (loose wheat smut)	*Ustilago nuda*	Mexico	Wheat, barley	PBW 396, HD 4672, AKDW 2997–16	1	15–25	6–7	15	Wunderle et al. (2012), Kassa et al. (2015)
	Semi-loose smut	*Ustilago nuda*	Egypt	Wheat	PDW 291, DDK 1009	7	16–22	4.5–8.3	15	Wunderle et al. (2012)
	Flag smut	*Urocystis agropyri*	Japan	Wheat	Pusa 44	3	18–22	6	55	Kashyap et al. (2020)
	Ball smut	*Tilletia laevis*	America	Barley, wheat	–	2	6–10	7	61	Muellner et al. (2020)
Bunt	Bunt of wheat	*Tilletia indica*	India	Wheat	*T. vulgare* Vill.	2	25–30	7.4	70	Pandey et al. (2018)
	Karnal bunt (partial bunt)	*Tilletia indica*	India	Wheat and barley	PBW343	2	25–30	7.4	70	Pandey et al. (2018)

	Hill bunt	*Tilletia tritici*	India	Wheat	Karnal sona	1	18–20	7	61	Bokore et al. (2019)
	Dwarf bunt of wheat	*Tilletia controversa*	Mexico	Wheat	HD29	3–10 weeks	18–20	6–7	60-8	Muhae-Ud-Din et al. (2020)

Table 4.2 Characteristic features of smut and bunt diseases in wheat

Disease	Types of smut	Nature (seed- or soil-borne)	Symptom initiation stage	Incubation period	Major nutrient requirement	Spore type	Organ infected	Yield loss (%)	References
Smut	Ball smut	Seed-borne	Flowering stage	3–6 weeks	Nitrogen	Teliospores	Grains and panicles	35	Ladhalakshmi et al. (2012)
	Stinking smut	Soil-borne	Seedling stage	5 weeks	Nitrogen	Teliospores	Gains	7–75	Shukla et al. (2018)
	Common bunt	Soil-borne	2–3 leaf stage	3 weeks	Nitrogen	Teliospores	Spikes	75–80	Mourad et al. (2018)
	Loose smut	Seed-borne	Flowering stage	3–6 weeks	Nitrogen	Basidiospores	Grains	50	Kaur et al. (2014); Abrahim (2019)
	Covered smut	Seed-borne	Seedling stage	12–18 h	Phosphorus, nitrogen, and potassium	Teliospores	Spikelets	45.9	Gad et al. (2019)
	Semi-loose smut	Seed-borne	Flowering stage	3–6 weeks	Nitrogen	Basidiospores	Spikelets	50	Abrahim (2019)
	Flag smut	Soil-borne	Twisted and bent seedling	5 h	Nitrogen and phosphorus	Basidiospores and Teliospores	Tillers, spikes and roots	20	Kashyap et al. (2020)
Bunt	Dwarf bunt of wheat	Seed or soil-borne	Seedling stage	21 days	Phosphorus, nitrogen, and potassium	Teliospores	Spikes	50	Dumalasova and Bartos (2016)
	Karnal bunt	Seed or soil-borne	Heading stage	3 weeks	Nitrogen	Teliospores	Grains and pericarp rupturing	40	Shukla et al. (2018)
	Bunt of wheat	Soil-borne	Boot stage	2–3 weeks	Nitrogen	Teliospores	Kernels	62	Sajjad et al. (2018)
	Hill bunt	Seed borne	Flowering stage	21 days	Nitrogen	Teliospores	Spikelets	25–37	Tagayev et al. (2018)

sporidia that initiate germ tube in stomatal opening of reproductive parts of wheat. The bunted grains usually enriched teliospores can stick to healthy grains or liberated in soil surface cause primary contamination in the next season (Pascoe et al. 2005; Turgay et al. 2020). In turn, teliospores germinate on the upper soil horizon and develop into promycelium. The identification of teliospores may be difficult upon infected wheat spike until harvesting. Besides these, teliospores undergo suicidal germination and in turn release a sufficient number of basidiospores under unfavorable conditions. However, in certain cases, germination of teliospores lag the susceptible stage, as a result, inoculum formation that remains viable in soil and initiates germination upon exposure to humid condition (Pascoe et al. 2005; Kumar et al. 2020; Turgay et al. 2020). Moreover, the mixing of teliospores in soil occurs through unintentional spore carrying agents (Birds, humans, animals) from the infected plant material and natural methods (wind currents and water flow). These teliospores can survive for several years in the hot desert and cold climate conditions and germinate under favorable conditions. Infection also occurs from allantoid sporidia, that is, air-borne propagules (Kumar et al. 2020; Turgay et al. 2020).

4.3.2 Hill Bunt

Hill bunt is caused by *T. caries* and *T. foetida* and is also known as stinking smut or European bunt (Muhae-Ud-Din et al. 2020). It reduces both the quality and quantity of grains and yield, respectively. The infected grains appeared darkened in color with a pungent fishy odor. Trimethylamine is responsible for odor and causes destructive loss during harvesting and storage. Commercially, these contaminated grains are used in ethanol production (Kochanova et al. 2004; Fang and Ramasamy 2015; Muhae-Ud-Din et al. 2020; Bishnoi et al. 2020).

The diseases' symptoms are not visible at the vegetative stage and appear after attaining the heading stage. The two types of smuts low smut (*T. caries*) and *T. foetida* (high smut) appear at the same time in the same inflorescence (Muhae-Ud-Din et al. 2020). Microscopic studies showed that the emergence and smut abundance can be only observed in the head of the smutted floret or infected caryopsis.

The ovaries in the infected inflorescence turn into white, large-sized, and comparability attain large pistil size. The pollens are pale yellow due to their sterile nature and stamen are evenly reduced than uninfected stamens. The promycelium producing from spore germination comes out, once the spore walls rupture (Fang and Ramasamy 2015; Muhae-Ud-Din et al. 2020). These hyaline unicellular primary sporidia fuse in pairs and form an H-shaped structure but remain attached to promycelium (Bishnoi et al. 2020). The binucleate structure after fusion produces secondary sporidia-bearing sickle-shaped hyphae. The infection occurs from spores that contaminate the grain surface during harvest instead of seed-borne mycelium. The infection is favored by low temperature (5–15 °C), humus-rich soil, clayey, sandy, acidic, high humidity, phosphorus, and potassium in non-irrigated land (Bishnoi et al. 2020; Muhae-Ud-Din et al. 2020) (Table 4.2).

4.3.3 Dwarf Bunt

The causal organism of dwarf bunt is *Tilletia controversa* synonym *T. brevifaciens* (Muhae-Ud-Din et al. 2020). It is also known by other names such as stunt bunt or short bunt. It was initially reported in Mexico but laterally the pathogen-infected wheat crops in others regions too (Murray and Wright 2007). The spores are viable for a short interval of time, once liberated in soil (3–10 weeks) and require optimum temperature (18–20° C), acidic or slightly neutral pH (6–7), and high humidity (60–80%). It is both soil- and seed-borne disease and has become viable for up to 10 years in the soil. However, symptoms are observed at early seedling/three-leaf phases (Muhae-Ud-Din et al. 2020), and the pathogenic inoculum takes 2–3 weeks for complete appearance and is enhanced with an elevated level of nitrogen, phosphorus, and potassium. The teliospores directly infect inflorescence structure and cause more than 50% in yield reduction (Dumalasova and Bartos 2016). The infected plants are appeared with excessive tillering and dwarfing structures. However, the spore germinates and initiates promycelium or germ tube to form 10–30 primary sporidia. The fungal hyphal growth developed mycelium on the growing region of seedling and infect inflorescence, and completely replace the kernel with spores (Murray and wright 2007; Pascoe et al. 2007). The infection takes place systematically and replaces reproductive structures with bunt ball. Pathogenic growth is mainly favored by low-temperature conditions and greatly impact winter wheat but also infect winter barley, triticale's, and *Secale* sp. in the absence of wheat (Wright and Murray 2007). The diseased grains release bunt balls and infect healthy wheat tillers. The specific pungent odor due to spores confirms the significant infection (Pascoe et al. 2007; Wright and Murray 2007).

4.4 Wheat Smut

4.4.1 Loose Smut of Wheat

Loose smut is a seed-borne disease caused by *Ustilago tritici* (Heterobasidiomycetes fungus) that mainly infects wheat crops during anthesis (Kumar et al. 2018a, b). It has been observed to spread to long-distance through carriers so and inflict moderate annual loss. It is reported from Poland, Romania, New Zealand, France, Bulgaria, Romania, China, and India. However, distribution of loose smut is presently confirmed worldwide, but initially, pathogen confined in regions of America, South Africa, and Australia (Abrahim 2019). In general, loose smut is much severe in the region of Durum wheat but is confined to be very common in other wheat cultivation regions with moist environment conditions (Wunderle et al. 2012). Pathogen races are not commonly found in bread wheat and are more restricted to durum wheat. Some predominant races like T3, T4, T14, T26, T32, and T33 are found in Canada at low incident level, whereas T14 and T32 are reported from wheat-growing regions of Turkey. These are mainly infected from seed, that is, seed spore remains to colonize internally in the embryo and diseased spike come out earlier from boot leaf than a healthy one. As far as seed-borne infection, there is no morphological variation observed in healthy and infected plants (Gad et al. 2019). At anthesis, infected spikelets are filled with black powdery mass, dry, and completely replace the reproductive parts of inflorescence. The spores are minutes, oval to spherical in shape, pale olive, 5–9 μm having small echinulate walls. The pathogen growth is highly favored at a temperature above 23 °C and maximum humidity approximately 60–80%. The *Triticum* spp. are the primary host for *U. tritici* except *for T. timopheevii.* The races that infect bread wheat are also reported to be pathogenic in some *Aegilops sp. Secale cereale* and *Triticosecale* (a triticale cultivar). The pathogenic susceptibility was also reported in other wheat wild relatives such as *Taeniatherum, Elymus, Haynaldia, Hordeum*, and *T. turgidum* (Gad et al. 2019; Abrahim 2019; Menzies et al. 2009).

Spore germination takes 5–7 days and constitutes dikaryon hyphae but almost takes 18–24 days to complete infection within the seed. The dormant mycelium of loose smut survives in the embryo of infected wheat grain. Fungus hyphae grow in nucellus and integument or intracellularly on the dorsal side of the caryopsis. The mycelium penetrates through the apical or central region and grows along with plumular bud in the embryo (Gad et al. 2019). This mycelium comprises largely microscopic, interwoven strands or tubular hyphae, which comprises filamentous structures that constitute the vegetative structure of the pathogen (Borgen and Davanlou 2001). At infection, fungi used up the host reproductive part and eventually systematically replace the embryo to colonize for the next generation. Mycelium cells are changed into smut spores at inflorescence or near head emergence, forming smutted heads. During the germination of infected seed, the mycelium establishment took place in the crown region and later on enters into the inflorescence region. The fusion of dikaryon nuclei leads to the formation of the diploid nucleus as teliospores mature. Such infected spores or matured teliospores from infected heads are liberated or blown away via rain, irrigation, pests, wind, and other biotic and abiotic entities to the healthy inflorescence (Abrahim 2019). Under favorable conditions, these spores germinate and form a mycelium colony, which penetrates stigma or ovary directly and re-established colonization inside new seed where they infect developing embryo (Gad et al. 2019). Earlier, both respiration and photosynthetic rates are higher in the infected plant but later it declines and results in loss in total biomass production of wheat. Moreover, upon maturation, it is difficult to separate healthy and infected seeds (Abrahim 2019).

4.4.2 Flag Smut of Wheat

Historically, the pathogen was reported from the United States, South Africa, Pakistan, Japan, Mexico, India, China, Chile, and Egypt. *U. agropyri* is a causal organism responsible for flag smut in wheat (Kashyap et al. 2020). In India, the severity is more than 75% in areas of Haryana, Punjab, and Himachal Pradesh. *U. agropyri* causes systematic infection and released sori in form of the long stripe with leaves at the fourth to fifth leaf stage and is considered the prime identification key of flag smut in wheat (Kashyap et al. 2011; Chalkley 2020; Kashyap et al. 2020). The pathogen infests itself in late seedling stages and tends to appears sori formation in leave sheath and leaf blades. Infected leaves pass through series of changes–twisted/rolling to dropping and ultimately wither. Latterly, leaves epidermis rupture and liberate numerous spores into the soil along with the disintegration of leaf tissues. The infected plants are dying out or stunted in which grains' formation is absent or shriveled that lack germination (Chalkley 2020). The spores are present in small globular structures consisting of three viable cells. These spores are lightly brown and globose in shape, whereas size ranges from 18 to 52 μm in diameter. The pathogenic spores are both seed- and soil-borne. Infection is influenced by soil pH, temperature, and humidity as well as poor cultural practices like deep sowing and susceptible varieties (Kumar et al. 2019). The infected seedling remains dormant and germinates beneath the soil, once the favorable environment condition reappears (Kashyap et al. 2011). It causes a 20% yield reduction via distorted inflorescence structures and affects seed quality traits (Table 4.2). The spore persists or remains viable in soil for up to 3 years and regenerate under favorable condition (Kashyap et al. 2020).

4.5 Molecular Diagnostic and Genetic Variability

Three races (T1, T10, and T11) of *Ustilago tritici* were identified from the Punjab State of India. The incidence of T1, T10, and T11 was 8.8, 30.0, and 61.3%, respectively (Rewal and Jhooty 1985). The composition of the loose smut population was not affected by climatic conditions but by the predominant wheat cultivars in a region. Partial infection of wheat heads was found to be due to environmental factors rather than to any specific race (Rewal and Jhooty 1985). The concept of introgression of previously unknown resistance into well-adapted wheat cultivars explores resistance and is over traditional control measures. Previously, the virulence of *U. tritici* differs considerably from wheat races including T9, T10, and T39 which are pathogenic on various Canadian bread wheat lines, whereas T5, T6, and T56 races possess virulence on few wheat lines (Randhawa et al. 2009; Aboukhaddour et al. 2020). Emerging polymerase chain reaction (PCR)-based detection techniques are highly sensitive, more reliable, and rapid comparable to traditional morphological and phenotypic methods. However, rDNA-ITS (ribosomal DNA internal transcription spacer) sequences have been known as the gold standard for the identification of pathogenic fungi (Ji et al. 2017; Kashyap et al. 2020). The chief advantages of ITS such as high accuracy, short length, high amplification signal rates, and universal primers availability. Besides these, ITS1 has a large copy number in the genome which provides a cushion of a large number of amplified fragments thus ensuring the liable identification from DNA of selected spores ($<$10) in PCR reaction (Kruse et al. 2017). Moreover, rDNA-ITS sequences have been well exploited to differentiate bunt and smut fungi. A primer designed from ITS1 regions for detection and differentiation of the *Tilletia* genus help to distinguish the related and unrelated smut and bunt pathogenic spores (Kashyap et al. 2020). Except these, ITS barcodes or signatures have been described as the important to detection of pathogenic fungi including *T. indica* and *T. tritici* (Kashyap et al. 2017). Another utilizes the role of effector in characterization, significant working, and deploy resistance gene carried out in modern resistance breeding. The mining of whole genomic sequence using bioinformatics tools and transcriptome information in *T. indica* provides data on seven pathogenicity-associated genes and overall 192 host–pathogen interactions. The expression and regulation activity of genes such as Ti57, Ti198, Ti12741, Ti10340, Ti2035, Ti2347, and Ti377 are associated with Karnal bunt and their role in sporulation mechanism, host pathogenic responses, elucidates via function genomics, and correlated strategies (Singh et al. 2020a, b; Kashyap et al. 2020). The genetic variability and race effectiveness also varied under different locations and regional climatic conditions. In the case of common bunt, *Bt5*, *Bt6*, *Bt8*, *Bt9*, *Bt10*, and *BT11* show strong pathogenic resistance in the Near East and North Africa where the poor effectiveness of resistance genes observed in European regions. Race-oriented resistance including *Bt8* and *Bt10* are more effective in North America but only *Bt10* has been widely accepted in current Canadian spring wheat (Aboukhaddour et al. 2020). To overcome these limitations such as the late appearance of diseases, selected floret infection, and huge spore number in the direct assessment of bunt resistance, marker-assisted selection (MAS) could be used. However, genotyping-by-sequencing (GBS) is one of the major efficient marker systems which have been used to analyze different traits used in plant breeding (Kumar et al. 2018a, b; Aboukhaddour et al. 2020).

GBS is a cost-effective approach that usually develops several SNP markers and helps to cover large genomic regions. Such genome-wide SNPs could be used in various genomic studies especially genomic selection, genome-wide association study (GWAS), and genetic diversity between races. Another association mapping is a new robust tool to recognize desired alleles that mediate the phenotypic alteration among wheat cultivars (Mourad et al. 2018). Recently, GWAS exposed a new resistance locus on chromosome 4D for the quarantine disease Karnal bunt in diverse wheat pre-breeding germplasm (Singh et al. 2020a, b). With GWAS, several resistance genes *such as Bt6, Bt7, Bt9, Bt10, Bt11, Bt12, Bt13*, and *Bt15* are efficient against the NCB race (Nebraska common bunt) which is chiefly virulent on *Bt1, Bt2, Bt3, Bt8,* and *Bt14*. The strong genetic variation observed among the genotypes that are very useful for selection to common bunt resistance in Nebraska wheat. Moreover, to enhance common bunt resistance, the utilizing of 123 SNPs associated with winter wheat resistance could be a reliable source for marker-assisted selection (MAS) by transforming them to Kompetitive Allele-Specific PCR markers. However, these SNPs should be validated in a different genetic background before using them for MAS. For more extension, see Mourad et al. (2018). Intensive and extensive sampling techniques were used to measure the genetic diversity of *Ustilago tritici*, using virulence and DNA polymorphism (Popovic and Menzies

2006; Thambugala et al. 2020). Datta et al. (2000) demonstrated intraspecific genetic variability analysis of *Neovossia indica* causing Karnal bunt of wheat using repetitive elements. Using marker help to understanding minor genetic variance among cross leads to the characterization of new minor alleles as the prime cause of variability. In this context, markers help to label identified alleles for sustained and durable expression of certain traits of disease resistance (Popovic and Menzies 2006).

4.6 Management Practices and Control Strategies to Overcome the Challenges of Smut and Bunt Diseases in Wheat

For several decades, around 90% of the crops are propagated by seeds; hence, they are considered as a potential source for diseases and their survival from season to season. Effective seed treatments and appropriate certification schemes have been practiced for healthy seed production; however, it is not easy to restrict the seed transmitted diseases. The yield loss can be reduced by applying chemical spraying under tight scheduling rather than after the incidence of diseases (Shakoor et al. 2014). The chemical residues lead to the development of pathogen resistance and also negatively affect the natural fauna. Finally, integrated approaches are only the effective strategy to check disease incidence, production, and maintenance of disease-free seeds in the crop field as well as storage (Hyde et al. 2019).

4.6.1 Host Resistance

The host resistance solely depends on or manifests via morphological and physiological traits. For instance, fungal epidemiology depends upon the moisture of flag leaf, hair count, stomatal distribution on glumes, flag leaf base, leaf sheath, and arrangement of spikelets. Several wheat resistance varieties were developed to mitigate the challenge of smut and bunts, for example, *U. nuda* (DWR 63, HS 277, KRL 210, MACS 2846, MACS 2971, DBW 41, GW 1255, HD 3065, HW 2308, HPW 348, VL 912, VL 914, VL 914, VL 924, VL 934, VL 941, WH 1107, MACS 5009, MACS 5004, MACS 2985, MACS 2980, MACS 2984, MACS 2981, HW 5304, HD 3016), *T. tritici* (DDK 1029), *T. controversa* (Sonop), and *U. agropyri* (Pusa 44) (Table 4.1) (Singh et al. 2017).

The diverse array of molecular markers such as diversity array technology, amplified fragment length polymorphism, simple sequence repeats, restriction fragment length polymorphism, and single-nucleotide polymorphism (SNP) were applied effectively to understand genetic linkage in durum. In loose smut, these marker types have been utilizing at low density to conduct quantitative trait loci (QTL) analysis. Therefore, increasing resolution can increase the precision of QTL mapping and allow the identification of new genomic regions affecting desirable traits (Kumar 2018). The role of double haploid production significantly accelarates fungal diseases identities discovered in past decades especially in new strain development ex; A preferred stock of DH line helps to identify newly loose smut resistance gene *Ut11* that confirmed resistance against T2 (a loose smut race) (Kumar 2018).

4.6.2 Physical Method

Physical methods are quite beneficial in the direction of environmental security without leaving any chemical or polluted residue in the environment (Aboukhaddour et al. 2020). The physical methods can be divided into three categories based on target or site of infection, physical methods on seed-borne pathogens, and physical methods on soil-borne pathogens (Singh and Pandey 2012; Bishnoi et al. 2020). Physical methods on seed-borne pathogens are the referred mechanical or hand controls those target the actual pest attacked and destroyed plant material of the plant. These procedures are practiced to get rid of or reductions of primary inoculums present in the plant material or seed (Aboukhaddour et al. 2020). The procedures or physical agents included under this category are hot water, hot air, or steam to eradicate the seed-borne infection. These methods have effectiveness against internally seed-borne diseases including the loose smut disease of wheat (Agarwal 2017). For instance, smut caused by the *Ustilago scitaminea* can be eradicated by the hot water 54–60 °C for 10 min.

The solar treatment is also proved to be very effective in regulating the loose smut of wheat by soaking the affected lot of seeds in the water for 4 h time period followed by drying in proper sunlight for a minimum of 4 h (Akhtar et al. 2008). Hence, this method is very useful in high-temperature areas. The solar heat treatment is used to eliminate the fungal pathogen, *Ustilago nuda,* from the wheat seeds. The thermal death point of embryo and fungus is very close; hence, utmost care has to be taken during practice. Soil provides the space and dead organic matter for the large number of plant pathogens that can target not only seeds but also the early stages of the plant such as the seedling stage (Abrahim 2019). Thus, soil treatment is more promising than seed treatment procedures. Moreover, soil treatment is safer as it mainly killing the pathogen. Soil solarization is the management tactic that involves the usage of polythene sheets to elevate the temperature 10–15 °C more than normal temperature (Akhtar et al. 2008). Soil solarization is an effective strategy to eradicate the spores of *T. indica*. The common bunt is favored in the cool soils; hence, the soils allow to warmer greater than 25 °C which allow to check the growth of bunt pathogen. The soil mulching with the polyethylene sheet has been a proposed method in the reduction of teliospore germination by high-temperature induction. However, it is very difficult at a very large scale commercially in developing countries (Bishnoi et al. 2020).

4.6.3 Chemical Method

Chemical seed treatments have been proved to be very effective against the bunt and smut diseases of wheat. The active ingredients of chemical compounds are mancozeb, carboxin, triazoles, triadimenol, triadimefon, and oxycarboxin for systemic and potential protections (Shukla et al. 2018). The chemical formulations against the loose smut diseases by carboxin 75% WP at the rate of 2–2.5 g/kg seeds, carbendazim 50% WP at the rate of 2 g/kg seeds, benomyl 50% WP at the rate of 2 g/kg seeds, carboxin 37.5% + thiram 37.5% DS at the rate of 3.0 g/kg, and tebuconazole 2% DS @ 0.2 kg/10 kg seed. The chemical composition against the flag smut of wheat disease can be achieved by using tebuconazole 2% DS at the rate of 0.2 kg/10 kg seed and carboxin 75% WP at the rate of 2–2.5 g/kg seed (Kumar et al. 2018a, b, 2019).

For the production of inoculums-free seeds against the Karnal bunt, the application of propiconazole spraying at the rate of 0.1% during the heading stage is preferred. The salts of sodium phosphate have an inhibitory role in teliospore germination. The proper timely of phosphate compounds inhibits or delays the teliospore germination under the infection of Karnal bunt disease (Turgay et al. 2020). The single spray for tilt (Propiconazole) at the rate of 0.1% has been recommended to regulate KB infection and produce the disease-free seed. At the heading stage, the fungicides such as bitertanol, carbendazim, fentin hydroxide, mancozeb, and propiconazole are at the heading stage for the effective control of Karnal bunt. The effective measures of chemical methods for common bunt disease are applied on the seed. The application of difenoconazole as seed dressing provides complete removal of common bunt disease (Kumar et al. 2019). It is also observed that carboxin and benzimidazoles have also been effective for seed treatments (Turgay et al. 2020). The systemic fungicide proves to be very effective against the dwarf bunt disease infecting the seedlings of wheat (Table 4.3).

4.6.4 Biological Methods

Biological control is the bio-effector strategy that involves the living organisms such as mites, insects, and phytopathogens to control the undesired pathogens (Asthana et al. 2016). The biocontrol agents have an antagonistic effect, decrease the negative impact of pathogens, or can modify the plant anatomy and physiology (Vajpayee et al. 2015). The beneficial microbes for the prevention of phytopathogens have additional benefits such as plant health improvement, plant growth, nutrient uptake and availability, and resistance to abiotic and biotic stresses. The spores of *Tilletia indica* are controlled by *Trichoderma longibrachiatum*, *T. harzianum*, and *T. viride* in wheat. The *Ustilago segetum* var. *tritici* caused loose smut of wheat was eradicated with treatments several bioagents on seeds such as *Trichoderma harzianum*, *T. viride*, *Gliocladium virens*, and *Pseudomonas fluorescence*. The teliospores germination of Karnal bunt can be checked by artificial inoculums of *Gliocladium catenulatum, G. roseum, G. deliquescence, Trichoderma viride,*

Table 4.3 Management strategies used to control the smut and bunt diseases in wheat

Disease	Types of smut/bunt	Physical strategy	Chemical strategy	Biological strategy	References
Smut	Covered smut	Seed treatment with aerated steam therapy at 50 °C for 1 h	Seed treatment with carboxin and thiram	Seed treatment with *B. axarquiensis* ESR 7 and *B. pumilus* ESR 21 suppresses smut disease	Borgen and Davanlou (2001)
	Semi-loose smut	–	Seed treatment with Captan, Maneb, PCNB, and Thiram	Treatment of seed sets with *Bacillus subtilis*	Borgen and Davanlou (2001)
	Stinking smut	Crop rotation, lesser irrigation	Seed treatment with warm water	Seed treatment with *Thuja* leaves	Borgen (2004)
	Loose smut	Hot air treatment in oven	Seed treatment with Vitavax	Treatment of seeds with *T. viride*, *T. harzianum*, *P. fluorescence*	Wunderle et al. (2012)
	Flag smut	Seeding in cool soil	Seed treatment with quintozene, fenfuram, triadimefon, triadimenol, and difenoconazole	–	Kashyap et al. (2020); Kumar et al. (2018)
	Ball smut	Early sowing of crop	Spraying of copper oxychloride or propiconazole at boot leaf and milky stages	Foliar spray of *Trichoderma* species	Muellner et al. (2020)
Bunt	Common bunt	Reduction in number of spores by brush cleaner, soaking of contaminated seeds with high-temperature water	A yellow mustard powder product (Tillecur) has been applied as a slurry to seeds before sowing	Isolates of *Streptomyces* and *Bacillus species* can reduce the teliospore germination. Cerall has also been used in wheat	Borgen and Davanlou (2001)
	Karnal bunt	Hot air oven treatment	Spray using propiconazole, agrozim, and bavistin	Foliar spray of *Trichoderma species*	Pandey et al. (2018)
	Bunt of wheat	Mulching and crop rotation	Foliar spray by propiconazole	Use of propiconazole along with	Pandey et al. (2018)

(continued)

Table 4.3 (continued)

Disease	Types of smut/bunt	Physical strategy	Chemical strategy	Biological strategy	References
				Trichoderma viride	
	Hill bunt	Grow seeds at high temperature	Seed treatment with chemicals, like carboxin and difenoconazole	Treatment with plant extracts of *Cannabis sativa*	Bokore et al. (2019)
	Dwarf bunt of wheat	Heat treatment given to seeds	Tillecur has been applied as slurry to seeds before sowing	Isolates of *Streptomyces* and *Bacillus species* used as seed treatment	Muhae-Ud-Din et al. (2020)

T. harzianum, and *T. koningii*. Several groups have reported the antagonistic impact of various bacteria on the *T. indica* (Vajpayee et al. 2015). One of the major reports in this regard is the inhibition of bunt fungus pathogen by 23 different bacterial strains by Asthana et al. (2016) (Table 4.3).

4.6.5 Cultural Methods

Cultural practices are the oldest and most frequently applicable eco-friendly disease management procedures (Saharan et al. 2016). These innovative approaches have excellent results in the past and are expected in the future also (Kumar et al. 2018a, b). Crop rotations with the selection of non-host crop plants like corn, soybeans, and sorghum reduce the population of fungal pathogens. This reduces the risk of infection in the nearby future or subsequent years. It has been also practiced that avoid early sowing to lessen the risk of flag smut disease by avoiding the contact of inoculums with warm moist soils. The cultural practices can only suppress the Karnal bunt disease development but are unable to completely eradicate the high survival rate (6 years) of teliospores in the soil as suggested by Bishnoi et al. (2020). The rotation with the non-host crop, less seeding rate, lower fertilizer, soil disinfection, and altering the irrigation schedule is the recommended cultural practices to regulate the Karnal bunt incidences (Fig. 4.2). Moreover, the study also indicated the low incidence of Karnal bunt under the zero tillage practice in comparison to the conventional tillage practices (Saharan et al. 2016) (Table 4.3).

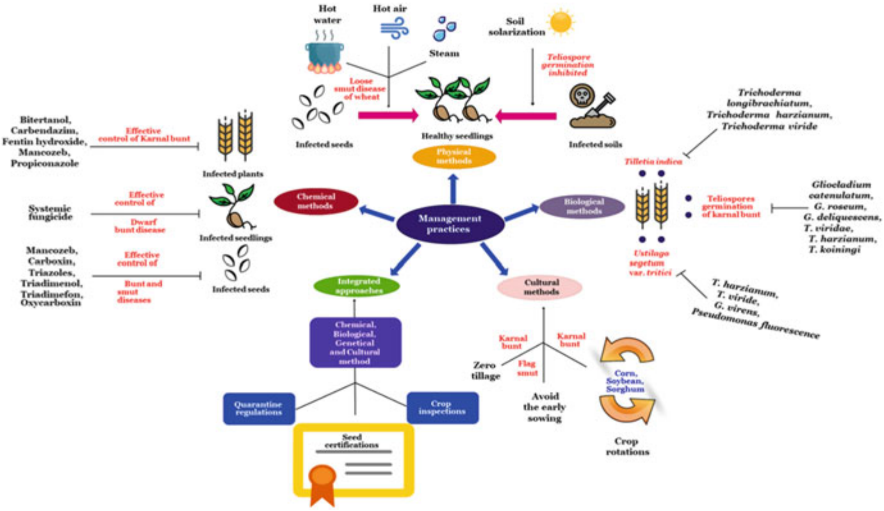

Fig. 4.2 Diagrammatic representation of various management practices to control smut and bunt diseases in wheat

4.6.6 Integrated Approach

The chemical, biological, genetic, and cultural methods are practiced in a compatible manner to frame the integrated disease management strategy for the production of healthy plants (Sansford et al. 2008). The exclusion of Karnal bunt can be achieved by preventing the invasion of pathogens to the uninfected regions, or farms by avoiding the contact of the pathogen with the crop. This strategy is based on the prevention of transmission traveling carriers employing natural barriers like oceans, mountains, and deserts. The exclusion can be achieved by delay the entry and provide some time for management on its arrival. The Karnal bunt was assumed to be originated in India and would spread to the Europe and United States. Therefore, preventive measures were taken to prevent its further spread to reach the United States, and further measures are taken to prevent the entry of pathogens to Europe and other parts of the world (Ykema et al. 1996; Sansford et al. 2008). The measures taken are seed certifications, crop inspections, and quarantine regulations to spread the pathogen. Similarly, certified seeds are inspected for the loose smut of wheat and whose very low level is tolerated. The growers who saved the untreated seed are most susceptible to the carrier of common bunt and smut diseases. The dwarf bunt disease has also been controlled by the strict international quarantine limits for further dissemination to non-infected areas (Mandal et al. 2006). Jasmonic acid and some other plant derivatives have been reported to induce the expression of wound inducible genes such as proteinase inhibitors showing antifungal activities (Diaz et al. 2002; Kumar et al. 2020). The increase in the proteinase inhibitors synthesis by jasmonic acid signaling pathways targeted the fungal protease activity and thus triggers the induced resistance (Mandal et al. 2006; Kumar et al. 2020).

4.7 Conclusion and Future Perspectives

Susceptibility of wheat to smut and bunt diseases needs multiple wheat resistance varieties. However, simultaneous maintenance of yield and disease improvement is always a slow-going breeding effort as enhancing introgression for disease resistance requires time. In recent years, the enhanced reports on the spread of quarantine important smuts and bunts diseases demonstrate how changes in germplasm and agronomical practices can greatly influence the behavior and severity of diseases. Step toward high-susceptible short genotype and elevated adoption of sustainable tillage practices have contributed to enhancing diseases caused by infected crop residues, stubble-borne, and water-dispersed pathogens. The host–pathogen specificity in these diseases pushes toward continuous check on arisen of new pathogenic race, virulence level/aggressiveness, or environmental adaptation. Existing reports indicate that fluctuation in weather condition plays dual function either it causes disease outbreak or helps pathogenic vectors in survival and distribution or restrict pathogenic growth.

Resistance to these pathogens (smut and bunt) is available with effective classical, physical, chemical, biological, and advanced molecular approaches. Furthermore, forecasting models need to be developed to predict the risk assessment, effect on host susceptibility, amount of inoculum and their distribution range, and weather condition favors on disease development. These models help in predicting decision about the proper time of spraying of fungicides and predicting the mycotoxins contamination at the final level. However, with variation in climatic changes, there might be an enhance in outbreaks of diseases in wheat crops, which could enhance potentially our liability on mycotoxins. The management of fungicides resistance includes avoiding continuous use of a single chemical or combining mycotoxins with various chemistries and integrating mycotoxins with nonfungicidal methods including recommended agrochemical and genetic resistance. The alternative control management practices help to decrease disease pressure and the selection load on pathogenic populations to develop fungicide resistance. Moreover, effective management strategies for maintaining seed-borne diseases are to select pathogen-free high-quality seeds. The possible and effective seed treatment with mycotoxins can manage the germinated seed and seedling infected from seed-borne pathogens that protect against common bunt and loose smut. The effective fungicides treatment must require to resolve the embryo infection in case of loose smut. The chemical guide must be revised from time to time due to the non-effectiveness of all fungicides as seed treating agents. In the case of biological management, the various derived microbial inoculums are attractive and promising options to control important diseases in an eco-friendly manner. Biocontrol approaches not only manage the disease severity but ensure the reducing level of pathogens up to harvesting. Field assessment of bioassay and culture shows much effectiveness and directly affects the biology of pathogenic fungi. Keeping in mind, the excessive use of chemical treatment pushes toward resistance or new race specificity, for example, teliospores of Karnal bunt are resistant to gastrointestinal enzymes, ozone, propionic acid, hydrogen peroxide, chloropicrin, and methyl bromide. In this context, using biochemical agents significantly enhances the performance of chemical safely and effectively without elevating input cost of disease management. However, breeding for genetic resistance either conventional or molecular practices is a resistance approach that creates chances for the short-term eradication of these problems. Nonetheless, complete resistance take account of efficient monitoring evaluation strategies for inoculation studies and resistance specificity, developing new pathogenic races in response to effective fungicides. Multiple gene resistance is mandatory for full-time resistance against multiple pathogenic races. However, the current agricultural system and climate change with emphasis on monoculture, globalized agriculture sector have driven the emergence of new pathogens with resistant races. With the advancement in knowledge on productivity-related interactions as well as the recent availability of wheat genome sequence, the breeding efforts are expected to take a bigger leap toward meeting the goal of improving wheat yield. No doubt, implementations of agronomical practices including classical, physical, chemical, and biological methods are efficient management approaches so far, but genetic resistance and use of molecular technique are also essential as well as complimentary for long-term disease management.

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5 Powdery Mildew of Wheat: Research Progress, Opportunities, and Challenges

Vijay Rana, Aashima Batheja, Ravi Sharma, Amit Rana, and Priyanka

5.1 Introduction

Crops have always been exposed to the perils of various biotic and abiotic stresses to varying degrees. Unfortunately, global climate change is expected to increase the incidence and severity of novel biotic stress factors, virulence evolvement, and broadening of the host range. Resistance response to pests and pathogens has a major role to play in safeguarding the yield potential of high yielding varieties.

Wheat (*Triticum aestivum* L.) is one of the most valuable food crops, playing a critical role in global food supply and defense, but its development is constantly threatened by a variety of diseases (Ma et al. 2014; Zhang et al. 2017a, b). The biotrophic fungus *Blumeria graminis* f. sp. *tritici* (Bgt) causes powdery mildew, which is one of the most severe diseases restricting wheat production in many regions of the world. *Blumeria graminis*, also known as grass powdery mildew, is a fungus that affects grass plants in the Poaceae family. Because of its economic impact on cereal crops (especially wheat and barley), it is considered one of the most important fungal pathogens, and it serves as a model system for studying biotrophic pathogens (Dean et al. 2012). Although the management of powdery mildew in realistic agriculture can vary depending on its economic significance, chemical control of the most common fungal diseases has been widely considered to be uneconomic (Wellings and Luig 1984). The ever growing world population

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demands well-organized plant disease management and control in agricultural production systems to ensure food security and safety (FAO et al. 2018). An effective and efficient mechanism for early warning and fast response is very essential to control phytopathogenic fungi. In this context, novel and effective diagnostic methods to minimize fungal plant disease are of utmost importance. Molecular assays can overcome many shortcomings of the conventional and serological methods in fungal diagnostics (Hariharan and Prasannath 2021). Given the expansion of powdery mildew's host range, a better understanding of the underlying genetics of reproductive barriers and self- versus non–self-identification between species of fungal plant pathogens could help predict hybridization events in various agroecosystems. The availability of large genome data sets will greatly support future research, and genome data will be a valuable resource when combined with experimental methods for analyzing hybrid fungal organisms. Over the last few decades, breeding achievements for disease resistance are likely to be equally important as breeding achievement for increased yield potential (Byerlee and Moya 1993). To maintain global food security by reducing the incidence of disease epidemics, great efforts are required to breed wheats with diverse and durable resistance. By reducing reliance on pesticides for disease and pest control, it also helps to protect the atmosphere and farmer's income. However, the most important thing to know is that host resistance might not be enough to control wheat powdery mildew disease; sound agricultural practices and judicious use of fungicides should also be considered. Looking at the ever growing economic importance of powdery mildew, information on various aspects pertaining to the pathogen study, host resistance, and integrated disease management is reviewed herewith.

To summarize, linkage drag, fungicidal resistance, fast jump and expansion in host range due to increased pathogenic variability are among the potential challenges for managing powdery mildew. On the other hand, advancements in the molecular diagnostic techniques for pathogen identification, cultivar development, artificial intelligence algorithms, and speed breeding protocols offer vast opportunities to tackle powdery mildew fungus in future.

5.2 Global Distribution and Host Range of Powdery Mildew Fungus

Wheat powdery mildew is found all over the world, although it is most prevalent in the northern hemisphere. It was found to be economically harmful in colder, coastal, or semi-continental climates until the Green Revolution. However, due to the introduction of intensive processing techniques, wheat powdery mildew has become a problem even in some hotter, drier areas in recent decades. This is largely due to the use of semi-dwarf cultivars, higher population densities, nitrogen fertilizers and irrigation, which result in thicker, more compact and more humid canopies (Bennett 1984; Cunfer 2002). The disease is more prevalent in areas where there is a lot of rain and the temperature is relatively low (Bennett 1984). Powdery mildew has been found in UK, Russia, Germany, Japan, Africa, and much of West Asia (Bennett

1984). Cooler areas of China, Japan, and Central Asia, as well as North and South America harbor powdery mildew as a common disease (Roelfs 1977; Saari and Wilcoxson 1974). The disease is more extreme in warmer, humid areas with mild winters, such as parts of South America and the southeastern United States. Powdery mildew is less common in areas where rain is regular and heavy because the spores are washed away from the leaves (Merchan and Kranz 1986). Powdery mildew is becoming increasingly problematic in India, especially in the northern and southern hills along with some areas in the northwest plain zone.

Regarding host range, powdery mildews (Ascomycota, Erysiphales) are known to infect over 10,000 dicot and monocot plant species around the world (Braun and Cook 2012). Many powdery mildew species cause economically significant diseases in agricultural and horticultural crops like wheat, barley, vegetable species, fruits, grapevine, etc. (Glawe 2008). Some forms of this fungus also affect various forest plant species (Marcais and Desprez-Loustau 2014). Many parts of the world have faced invasion by some powdery mildews (Kiss 2005; Desprez-Loustau et al. 2010), leading to threat to plant health and biosecurity (Desprez-Loustau et al. 2010). *Blumeria graminis* infecting cereals and *Erysiphe necator* infecting grapevine, two important powdery mildew species, have served as model species in plant pathology research (Gadoury et al. 2012; Bindschedler et al. 2016). On the other hand, in wild plant pathosystems (Susi et al. 2015), interactions between *Podosphaera plantaginis* and its host *Plantago lanceolata* have long been the focus of many studies.

B. graminis has eight formae speciales that are each specialized on particular host species among the wild and cultivated grasses. However, the host range of *B. graminis* cultures isolated from cereals in Israel is wider than that of isolates from elsewhere in the world (Eshed and Wahl 1970). This likely reflects the greater diversity of *B. graminis* hosts in the Middle East, which is believed to be the center of origin and diversity of the wild ancestors and relatives of cultivated cereals (Wyand and Brown 2003).

Braun (1987) discovered 18 genera and 435 species of the powdery mildews, which are able to infect a wide variety of hosts from several tree species to herbs. Up to 9838 species among 1617 genera, 169 families, and 44 orders of angiosperm plants have been found to be the host of powdery mildews (Amano 1986). Thus, the powdery mildew fungus is one of the most significant plant pathogens. Host range of these is exclusively limited to angiosperms and they have never infected ferns or gymnosperms.

5.2.1 Yield Losses and Adverse Effects

The wheat powdery mildew, *Blumeria graminis* (DC.) E.O. Speer, f. sp. *tritici* Em. Marchal (Bgt) (syn. *Erysiphe graminis* (DC) f. sp. *tritici*), is the sixth most important fungal pathogen in wheat, according to Dean et al. (2012), and is responsible for the eighth highest yield loss due to pests and pathogens worldwide (Savary et al. 2019). Powdery mildew may occur year-round in many wheat-producing regions, with output losses of up to 35%, 62%, and 40% in Russia, Brazil, and

China, respectively (Mehta 2014). Attributes of Bgt, such as short life cycle, airborne spores equipped for voyaging significant distances, and above all sexual recombination for producing new virulences, advance quick spread and variation.

The relationship of mildew severity to yield loss depends on the crop growth stage, methodology used for disease assessment, timing, canopy position, and intensity of epidemic pressure. Several studies have elucidated this relationship in experimental field settings. Large and Doling (1962, 1963) found the best growth stage for relating yield loss in winter wheat to mildew severity (measured as total photosynthetic leaf area covered by mildew pustules) was at full heading. The grain yield loss was found to be proportional to twice the square root of severity, using a data set in which mildew severity from natural epidemics in unprotected plots ranged from 0% to 16%. However, Dutch researchers noted an effect of canopy position (Rabbinge et al. 1985). They observed that if preflowering infections were in upper canopy levels or distributed uniformly throughout the canopy, even low severity (approximately 4% of leaf area covered by mildew) could cause as much as a 10% yield loss, with the disproportionate impact attributable to reductions in assimilation and transpiration rates. The fungus reduces the amount of photosynthates available in leaves, lowers the leaf assimilation index, and has a negative impact on grain yield components (Bowen et al. 1991; Henry and Kettlewell 1996; Samobor et al. 2005). Infection during the tillering, stem elongation, and booting phases has a significant impact on yield, particularly when it occurs early (Bowen et al. 1991), resulting in lower kernel weight and yield.

Grain yield losses associated with wheat powdery mildew infection can exceed upto 40%, with the most extreme losses occurring before or after flowering, when the flag leaf becomes infected (Royse et al. 1980; Li et al. 2011; Alam et al. 2013). *Blumeria graminis tritici* has been confirmed to reduce wheat yield by 10–15% in most cases, and up to 50% in extreme cases, according to recent studies (Jia et al. 2018; Singh and Sharma 2020).

5.2.2 Symptoms, Disease Cycle, and Epidemiology

Powdery mildew occurs as thick, white powdery fungal fruiting bodies on the leaf surface, as well as on the awns and glumes under favorable conditions. The symptoms usually progress from lower to upper leaves, but infection can happen at any time during the season depending on weather conditions. Rapidly developing tissue is more vulnerable to infection, so plants in their early stages of development and after nitrogen application are more likely to have a more severe infection. Fungal colonies grow in size and eventually merge. The region around the lesion, as well as the leaf's reverse side, turns yellow to brown. Older infections turn grey and may develop black fruiting bodies, known as chasmothecia (formerly known as cleistothecia), that appear as black specks. Infections that are moderate to severe are able to cause necrosis. From a distance, a powdery mildew-infected crop seems yellow and exhibits symptoms similar to that from water logging or nutrient deficiency.

Powdery mildew has a fast infection period and develops millions of spores (conidia), allowing it to spread quickly through the crop. The cycle of spore germination, infection, and eventual spore development can be completed in as little as 5 days under ideal conditions (cold and humid). With changing temperatures, there is significant variation in spore production and the latent period (time between infection and spore formation). Optimum temperature range of 15–22 °C is required for disease development. Lower temperatures (5–10 °C) cause the infection cycle to take 2–3 times longer than at 20 °C, resulting in delayed symptom expression and reduced spore formation.

Infection and sporulation are stalled at temperatures above 25 °C. If the infection has taken hold, the white dense powdery mildew conidia are dispersed across the crop by the wind as a secondary infection. The disease thrives in humid, mild weather with a moist canopy. Since the fungus does not need wet leaves to infect them, rain is not needed for disease transmission, but it does promote canopy humidity. Infection becomes even more common when the relative humidity rises to 90%, but does not occur when the leaf surfaces are wet (e.g., in a rain shower). Heavy rain can wash spores from the leaf surface, slowing disease progression temporarily.

When environmental conditions are unfavorable, infection process is decelerated. These entail periods of low canopy humidity and temperatures above 25 °C, as well as dry and warm weather conditions. Experiments have shown that exposure to 25 °C for 6–12 h will defer disease development by 4–6 days and curtail severity by 30–50%. Exposing to 25 °C for more than 24 h dissuades disease development. The fungus endures the winter in the form of cleistothecia on wheat straw or mycelium on infected wheat. Under cold, humid conditions, spores germinate and infect plants. The two forms of pathogenic inoculum for infection are asexual conidia and sexual ascospores. A specialized germ tube is formed when conidia or ascospores adhere to a photosynthetically active wheat leaf surface, and it elongates to form a thread-like hypha with appressoria in as little as 2 h (Acevedo-Garcia et al. 2017). The digitate hypha then produces a penetration peg and grows into a haustorium, allowing the host epidermal cell to be breached (Glawe 2008). Bgt can thrive in the absence of a living crop due to the ascospores produced by chasmothecia/cleistothecia. Jankovics et al. (2015) characterized the mechanism of ascosporic infection in Bgt. The outbreak process is aided even further by mild temperatures (10–22°C) (Beest et al. 2008).

Powdery mildew can live between seasons by growing on volunteer wheat plants (green bridges) and wheat stubble. The presence of green wheat during the year in a given area offers an avenue for biotrophic pathogens such as rusts and powdery mildew to infect new emerging crops, resulting in higher levels of disease inoculum spreading at the start of the season. In some areas, favorable summer/autumn weather can allow for the production and persistence of regrowth. After autumn rains, the fungus lives as fruiting bodies on wheat stubbles (from previously infected crops) that release spores. Once a crop is affected, disease can be transmitted over great distances through light, airborne spores from fluffy white outbreaks on leaves.

5.2.3 Pathogenic Variation and Evolutionary Analysis in *Blumeria Graminis*

The classification of *B. graminis* in numerous *formae speciales* was presented for the first time by Marchal (1902) and it is utilized to characterize "forms" that are morphologically not discernable but infect different plant species (Schulze-Lefert and Panstruga 2011). According to this definition, a forma speciales does not necessarily represent a distinct evolutionary unit (heredity). However, the specialization on different hosts implies, at least in theory, barriers to gene flow between different ff. spp. and, therefore, defines ff. spp. as separately evolving lineages, which is the only necessary property of a species according to the unified species concept (de Queiroz 2007). The advent of next-generation sequences has provided researchers the ways that how species evolves and attempts to reconstruct the tree of life with huge amount of data. One consequence of this has been the full recognition of the difference between gene trees and species trees and of the processes that cause it (incomplete lineage sorting and lateral gene flow) (Posada 2016). These processes have different relevance in different systematic groups and at different timescales in the same group. Menardo et al. (2017a, b) have suggested to reconstruct evolutionary histories with genomics data using a diverse set of methods that are suited for lineages with a different level of divergence and isolation. The application of these methods to the grass powdery mildew *B. graminis* has allowed these researchers to disentangle a complex evolutionary trajectory that includes coevolution between pathogen and host, host jumps, and fast radiations. In the recent times, *B. graminis* has evolved eight distinct *formae speciales* (ff. sp.) that display strict host specialization.

During the past few years, powdery mildew has emerged on triticale, the artificial intergeneric hybrid between wheat and rye in the early 2000s in many locations, probably due to a host range expansion of the wheat forma species, *Blumeria graminis* f. sp. *tritici*. Many triticale cultivars have been found to be highly susceptible to powdery mildew, mainly in seedling stage, revealing a probably narrow genetic basis for powdery mildew resistance genes (Pm). Moreover, as *Blumeria graminis* is an obligate biotrophic fungus, it is very time consuming and difficult to maintain powdery mildew isolates for a nonspecialized laboratory and evolution of populations can occur. Interspecific crossing of wheat, resistant to powdery mildew in seedling stage, and rye has been initiated to introduce potentially interesting genes for resistance in triticale. Troch et al. (2014) utilized *B. graminis* isolates sampled from triticale, wheat, and rye from different breeding regions in Europe. Pathogenicity tests showed that isolates collected from triticale are highly pathogenic on most of the tested triticale cultivars. Moreover, these isolates were also able to infect several wheat cultivars (their previous hosts), although a lower aggressiveness was observed compared to isolates collected from wheat. Phylogenetic analysis of nuclear gene regions identified two statistically significant clades, which to a certain extent correlated with pathogenicity. No differences in virulence profiles were found among the sampled regions, but the distribution of genetic variation demonstrated to be geography dependent. A multilocus haplotype network showed that haplotypes pathogenic on triticale are distributed at different sites in the network, but always clustered at or near the tips of the network. This study revealed a genetic structure in *B. graminis* with population differentiation according to geography and host specificity. In addition, evidence is brought forward demonstrating that the host range expansion of wheat isolates to the new host triticale occurred recently and multiple times at different locations in Europe.

5.2.4 Conventional and Modern Methods for Pathogen Identification

In the field of phytopathogenic fungal diagnosis, several advancements have been made. Traditional diagnosis of fungal diseases relied on visible morphological structures such as sclerotia, conidia, or mycelia found on the outer surfaces of flora or by the symptoms produced after infection by the fungal pathogens (Nezhad 2014; Tor and Woods-Tor 2017). These widely used traditional approaches including isolation, culturing, reinoculation, and biochemical as well as microscopic techniques are believed to be the foundation for diagnosis of fungal diseases (Tan et al. 2008; Sharma and Sharma 2016). These methods are time consuming and requires deep knowledge and experience in plant fungal taxonomy and pathology (Pryce et al. 2003; McCartney et al. 2003; Sharma et al. 2017). Diagnostic approaches based on antigen-antibody binding have poor affinity, sensitivity in assays, and possible interference caused by contaminants (Meng and Doyle 2002). Further, due to high inconsistency and phenotypic serological plasticity of fungi also leads to ineffective detection of fungal plant pathogens (Luchi et al. 2020). As a result, it is critical to introduce and improve innovative and efficient diagnostic methods to combat plant fungal diseases. Hence, plant-fungal diagnosis has shifted toward molecular methods which are rather more useful in pathogen identification and quantification. Moreover, molecular assays can solve the limitations of traditional and serological approaches.

In context to early plant disease detection, polymerase chain reaction developed in the mid-1980s has proved to be a fundamental technique in molecular biology. PCR allows small amounts of the DNA fragments to be amplified in a semi-conservative way (Mullis and Faloona 1987) and determination of taxonomical status of fungal isolates. Detection techniques are mainly based on the presence of specific fragments of fungal DNA or the amplicons. A primer pair was developed by Zeng et al. (2008) to amplify *B. graminis* f. sp. *tritici* DNA. Chen et al. (2015) used BF-F1/R PCR primers to create a single 464-bp product for multiplex detection of three pathogens. Later, a nested PCR assay was designed by Zeng et al. (2010). Its sensitivity was increased by using external and internal primer pairs. The internal transcribed spacer (ITS) DNA marker is commonly used for fungal identification, but only three of four powdery mildew samples yield a clear result. In contrast to ITS, some genes provide improved identification, according to a search for new markers (Kashyap et al. 2017). Others fail because of problems with amplification and sequencing, as well as a lack of insightful variability. Some of the powdery mildew species are easy to see but hard to identify. There is room for improvement in current identification and phylogenetic reconstruction methods. With varying degrees of success, working protocols for amplification and sequencing of seven genes (actin, tubulin, calmodulin, Chs, elongation factor 1- [EF1-], Mcm7, and Tsr1) have been established. When used alone and in conjunction with ITS, Mcm7 proves to be the most useful for phylogenetic reconstruction of closely related, phylogenetically young, powdery mildew species. As a result, Elingham et al. (2019) recommended that Mcm7 in addition to the ITS be used as the most appropriate candidate gene for powdery mildew diagnostics. Even though molecular diagnostic approaches have advanced significantly in recent years, there is still a long way to go in terms of their development and application in plant diseases. Aside from the aforementioned methods and technologies, studies using artificial intelligence for plant disease detection have begun to emerge (Singh and Sharma 2020).

5.3 Identification of Resistance to Wheat Powdery Mildew

Genes for resistance to wheat powdery mildew, whether qualitative or quantitative are termed Pm genes. Artificial inoculations in controlled environments of greenhouses or growth chambers are mostly used to carry out genetic studies on race-specific Pm genes. Isolates are multiplied under most appropriate conditions in a growth chamber and, thereafter, used to inoculate wheat seedlings growing under greenhouse conditions (Hua et al. 2009; Li et al. 2009). This method ensures the elimination of variation in disease reaction response that can be observed due to the heterogeneity of the pathogen population in the field, but has limitation of interpretation of results to a single isolate or to a small sample of isolates. Because *B. graminis* f. sp. *tritici* is an obligate parasite, propagation of inoculum can only be done on living plant tissues. Individual isolates with known virulence spectrum are usually maintained on detached segments of leaves of universally mildew-susceptible wheat variety. The leaves are floated on agar medium amended with a low concentration of the fungicide benzimidazole, which slows leaf senescence (Parks et al. 2008). Isolates can also be increased on seedlings grown in pots enveloped in plastic bags with a small opening at the bottom for gas exchange. Powdery mildew spores are short lived but have a short generation time (approximately 1 week) and can reproduce in very large quantities (Bushnell 2002).

5.3.1 Types of Resistance

Genetic resistance is believed to be the most useful, cost-effective and environmentally sustainable method of controlling powdery mildew. Different plant resistance levels to a particular pathogen species are determined largely by how the pathogen interacts with the host, which can be broad spectrum (e.g., quantitative basal resistance) or race specific (R gene-based resistance). In this sense, race-specific resistance is often related to life-long immunity and reflects resistance at all times, while quantitative resistance is typically effective only after seedling stage. There are, however, certain instances in which such laws do not apply. The nucleotide-binding site leucine-rich repeat (NLR) type receptors are a well-known class of resistance proteins encoded by plant R genes (Deyoung and Innes 2006; Jones and Dangl 2006). Wheat powdery mildew resistance gene, *Pm21,* generates a standard NLR protein, but it confers broad-spectrum Bgt resistance at both seedling and adult plant levels (He et al. 2018). Some genes, such as the adult-plant resistance (APR) gene, LR22a, are involved in quantitative resistance. However, this gene also encodes an NLR protein (Thind et al. 2017). Furthermore, in wheat lines carrying Pm6 and Pm8, decoupling of race-specific resistance and life-long resistance was observed, with resistance present at the adult plant stage but not at seedling stage (Golzar et al. 2016). Since few Pm genes have been sequenced and understanding of the genetic basis underlying quantitative resistance to disease is still in its early stages, resistance modes included in resistance breeding schemes (Ning and Wang 2018) are commonly referred to as race-specific resistance or broad-spectrum resistance.

In plants, reactive oxygen species (ROS) play an important role in their response to biotic stress. The disparity in subcellular localization of H_2O_2 and O_2 between two powdery mildew susceptible and resistant wheat cultivars was found to be correlated with different downregulation of the genes accounting for superoxide dismutase and catalase. These findings indicated that reactive oxygen species (ROS) are involved in the process of cell death in wheat roots caused by the powdery mildew fungus.

5.3.2 Race-Specific Resistance

The existence of a major resistance gene (R gene) and cognate pathogen avirulence gene (Avr gene) causes race-specific resistance (Flor 1971), and this has proven to be the underlying theory for resistance breeding in wheat for several decades (Wang et al. 2005; Lillemo et al. 2010; Shamanin et al. 2019). Regardless of plant level, the resistance (R) gene codes for a receptor that is activated by a pathogen effector. The dominant R gene and dominant Avr gene are predicted to produce a resistant outcome, while the interaction of a recessive allele in one or both of the host and pathogen leads to susceptibility. Only six (*Pm2*, *Pm3*, *Pm8*, *Pm17*, *Pm21*, and *Pm60*) of the collection of powdery mildew resistance (R) genes (*Pm* genes and temporarily assigned genes) and alleles reported in the wheat genome have been cloned so far, all encoding NLR class proteins. (Yahiaoui et al. 2004; Cao et al. 2011; Hurni et al. 2013; Sánchez-Martín et al. 2016; Xing et al. 2017; He et al. 2018; Singh et al. 2018; Zou et al. 2018; Kang et al. 2020). The host still has complete resistance to the pathogen as a result of the gene-for-gene interaction. When the prevailing pathogen genotype alters, however, R gene resistance is no longer reliable. As a result, race-specific resistance genes often trigger "boom–bust" disease cycles over time, with the disease being dominated by a new gene for a period of time before being resolved by adaptation in the plant pathogen. Strategies based on gene pyramiding with a variety of *Pm* genes simultaneously, regional distribution, or temporal allocation of R genes are suggested for robust breeding to extend the durability of race-specific resistance (Li et al. 2014; Burdon et al. 2014). Because of the genetic variation in the pathogen population, the concurrent existence of various pathotypes in natural surroundings increases the risk of disease outbreak. As a result, pyramided genotypes can fail to stop pathogenic intrusion for extended periods of time and ultimately become ineffective once these genes are overcome. In plant breeding, allele mining has been proposed as a way to bring value to gene stacking (Bhullar et al. 2010b). Genetic variation in a phenotype or trait is caused by allelic diversity at a resistance locus. For example, combining lines with different alleles of a single resistance gene (*Pm3*) has demonstrated to be an effective technique for the successful and long-term use of race-specific genes (Brunner et al. 2012; Ma et al. 2016), which may be an evolutionary advantage to selection by particular pathotypes (Yahiaoui et al. 2006). Allele mining of *Pm3* gene present in wheat on chromosome 1AS resulted in the identification of 20 functional alleles. Seventeen of them have been cloned. These 17 alleles share 97% of the homology (Yahiaoui et al. 2006; Bhullar et al. 2010a). Comparative analysis between *Pm3* loci of wheat and two rye (*Secale cereale*)-derived powdery mildew resistance genes *Pm17* and *Pm8* suggests that *Pm17* and *Pm8* of the 1RS translocation are evidently allelic and are orthologous to *Pm3* (Singh et al. 2018). In addition, allele mining of *Pm17*/*Pm8* is a powerful indicator of the enhancement of the wheat powdery mildew gene pool by introgression of various rye germplasm alleles.

Evolutionary study suggested that *Pm3* alleles originally come from *Pm3CS*, a susceptible allele in domesticated tetraploid wheat and widely found in bread wheat cultivars (Yahiaoui et al. 2006). Transgenic lines with *Pm3* allelic series gave greater resistance to powdery mildew in field tests compared to parental lines with only one *Pm3* allele (Koller et al. 2018). This increase in resistance came from an allelic conjunction and an additive interaction of alleles.

5.3.3 Quantitative (Broad-Spectrum) Resistance

Arbitrary terminology for quantitative resistance includes the terms "partial resistance," "horizontal resistance," "background resistance," "slow-mildewing," or "APR" to represent resistance in plants after seedling stage (Bennett 1984; Tucker et al. 2007). Thus, unlike race-specific resistance, quantitative resistance has very distinct characteristics. This type of resistance does not often result in a total absence of infection; instead, it lessens fungal sporulation and duration of infection (Poland et al. 2009). Quantitative trait locus (QTL) mapping is an effective method of detecting quantitative resistance to powdery mildew. Over 100 Bgt QTLs have indeed been mapped to homoeologous groups from various molecular mapping studies, some of which are positioned at the same marker intervals (Kang et al. 2020). New QTL identification is still predicted to boost with the development of a high-resolution genetic map aided by genome-wide genotyping markers. The single nucleotide polymorphisms (SNPs) array provides a high-performance platform for the molecular breeding of quantitative traits and is effective for the discovery of genetic variants. They have been used to map the disease resistance loci and identify four QTLs in the elite wheat line Zhou8425B (Jia et al. 2018).

A fully sequenced and annotated wheat genome (Appels et al. 2018) will also help in the future to explore certain functional gene groups underlying powdery mildew QTLs mapped to a similar region. Most studies have found that quantitative resistance is more durable and robust than qualitative resistance to pathogen evolution, provided that there is almost no selection pressure on the pathogen (Liu et al. 2001; Li et al. 2014). Some powdery mildew APR genes provide broad efficacy to multiple pathogens, a trait much desired by breeders.

Isolation of the APR genes, *Pm38* and *Pm46,* found a single gene encoding the ATP-binding cassette (ABC) transporter (Krattinger et al. 2009) and the hexose transporter (Moore et al. 2015), respectively, at the multipathogenic resistance locus, which imparts dual resistance to wheat leaf rust and strip rust along with powdery mildew. Besides these, many other ground-breaking findings highlight the relevance of ABA and sugar signaling in modulating plant immune systems not mentioned in the zigzag model. The complex genetic basis makes it difficult for breeders to manipulate quantitative resistance. If quantitative resistance has an impact on basal nonhost defense, then it is fair to expect that it will be more durable (Mundt 2014). Johnson (1981) assumed that the forecasting of durability is complicated to implement because the interpretation is made after the allocation of the cultivar to a favorable environment. As a result, a plant breeder does not know how a cultivar will perform in the long term until a multiyear field trial is conducted.

Multifaceted genetic interactions of race-specific resistance and quantitative resistance to powdery mildew are normally found to co-exist in a given cereal cultivar (Miedaner and Flath 2007). Some studies have already reported that the promising durability of qualitative R genes can be boosted when combined with quantitative resistance (Brun et al. 2010). This provides a commitment for breeding cultivars with long-lasting resistance, taking advantage of both types of resistance, but yielding far beyond additive benefits. But the assessment of the genetic effects in the blending of both types of resistance in a cultivar is difficult because quantitative resistance can only be evaluated when the host lacks qualitative resistance genes (Miedaner and Flath 2007; Burdon et al. 2014).

5.3.4 Recessive Resistance

Resistance genes or QTLs have been considered to confer resistance to disease, but susceptibility genes have also been identified to control disease reactions in plants. Silencing of these susceptibility factors has also been proven to contribute to resistance to powdery mildew in monocots and dicots (Consonni et al. 2006; Wang et al. 2014; Appiano et al. 2015; Pessina et al. 2016). *MlO* (Mildew-Locus-O) is a very well-explored type of powdery mildew susceptibility gene. It was first reported in barley toward *Blumeria graminis* f. *hordei* (Bgh) in 1942. The recessive mutation of the *MlO* gene is observed as an efficient and durable source of resistance (*MlO* resistance) to Bgt. In barley, the *mlo*-mutated gene has conferred resistance to most Bgh isolates for more than 30 years (Jorgensen 1992). However, hardly any natural incidence of a *mlo* gene has been noticed in wheat (Acevedo-Garcia et al. 2017).

Recently, *TaMlo* mutants have been produced on the basis of different technologies, all showing good resistance to Bgt (Wang et al. 2014; Acevedo-Garcia et al. 2017). *Mlo* genes are largely conserved in the plant kingdom, with comparative studies showing that wheat and barley have conserved similarity in the genome structure. Similarly, host-specific pathogens Bgt and Bgh also coevolved with each host and showed gene collinearity (Mayer et al. 2011; Oberhaensli et al. 2010). The functional annotation of barley *Mlo* genes should be able to assist in the exploration of wheat mlo-based resistance, as *TaMlo* shows approximately 88% similarity to barley (Elliott et al. 2002).

Powdery mildew-specific resistance separates *MlO* from another type of negative regulator, enhanced disease resistance 1 (EDR1) (Zhang et al. 2017b), a mutation that also causes powdery mildew resistance but exhibits more general resistance (Huckelhoven 2005). EDR1 resistance is another type of disease resistance mechanism, where mutation also causes resistance to powdery mildew. Zhang et al. (2017b) created *Taedr1* mutants by editing wheat EDR1 with regularly interspersed short palindromic repeats/CRISPR-associated 9 (CRISPR/Cas9) technologies. Bgt resistance exhibited by the mutant plants, thus, generated was found to be independent of mildew-induced cell death. This study clearly highlights the possibility of using EDR1 as an ideal target for improving resistance to powdery mildew through the use of new genome-editing tools.

5.4 Breeding and Deployment of Wheat Powdery Mildew Resistance

5.4.1 Management Strategies: Deployment of Wheat Powdery Mildew Resistance

Due to the significant yield-limiting economic effects of powdery mildew, the improvement of disease resistance is given due importance in most wheat breeding programs worldwide. During the 1996 survey, it was reported that powdery mildew resistance was one of the top four genetic disease resistance priorities in 115 winter and voluntary wheat breeding programs worldwide (Braun et al. 1997). Powdery mildew fungi of cereals are considered by the Fungicide Resistance Action Committee (FRAC) to be plant pathogens at high risk of developing fungicide resistance (FRAC 2005). It is, therefore, particularly important to ensure a broad and effective genetic basis for resistance in cultivars to this disease. Breeding of resistant cultivars is considered to be the most economically sound and environmentally safe method of eliminating the use of fungicides and reducing crop losses due to powdery mildew. The most common breeding strategy was the use of major genes conferring hypersensitive resistance types. This form of resistance, also known as race-specific resistance, follows the gene-for-gene model (Flor 1955), in which a corresponding avirulence gene (Avr gene, now often referred to as elicitor) is present in the pathogen for each resistance gene (R gene) in the host plant. The interaction between the host R gene and the pathogen Avr gene determines whether there will be a compatible (susceptible) or incompatible (resistant) reaction in the host.

Temporal and spatial continuity in the use of cultivars with race-specific resistance genes generally provides immunity or near disease immunity, but exerts selection pressure on the pathogen population. This causes the pathogen to develop corresponding virulence, which reduces the life span of these cultivars to a few years. This scenario occurred with most commercially grown wheat varieties (McDonald and Linde 2002). Increased virulence and changes in virulence frequency are strongly influenced by resistance genes borne by cultivars grown in a particular area. Major genes can confer more long-lasting resistance to disease if they are deployed using disruptive directional selection. Simultaneous deployment of different *Pm* genes using cultivar mixtures (Mundt 2002), isolines with different resistance genes (Zhou et al. 2005), or pyramiding different major genes into a single cultivar (Liu et al. 2000) increases the number of mutations needed in the pathogen population to overcome all existing host resistance genes.

Use of cultivar mixtures should be the ideal target for the control of powdery mildew due to the relatively shallow dispersal gradient of the mildew pathogen and the large number of pathogen generations per crop season. Manthey and Fehrmann (1993) reported that the levels of infection with powdery mildew, leaf rust, and striped rust were significantly reduced with the use of cultivar mixtures and the greatest reduction in disease development was observed for powdery mildew. Zhou et al. (2005) have developed near-isogenic lines (NILs) with powdery mildew resistance using molecular markers. Amplified fragment length polymorphisms (AFLPs) were used to assess the similarity of NILs to their recurrent parent, and AFLPs and Pm-linked microsatellite markers were used to select powdery mildew resistance.

Pyramiding multiple resistance genes in local cultivars is an effective strategy to increase the durability of powdery mildew resistance. Three powdery mildew resistance gene combinations *Pm2* + *Pm4a*, *Pm2* + *Pm21*, *Pm4a* + *Pm21*, and *Pm4a* + *Pm21* have been successfully integrated into the elite wheat cultivar "Yang158" by means of markedly aided pyramiding (Liu et al. 2000). In another example, Murphy et al. (2009) reported 13 two-gene and 6 three- and four-gene pyramids, developed using a combination of marker-assisted selection and duplicate haploid technologies. The combination of various resistance genes in a single genetic background is expected to provide broad-spectrum resistance through individual gene action and complementation between resistance genes. However, the detection and screening of several resistance genes in the same population at the same time as conventional methods are hardly applicable in practice. Recently, Koller et al. (2018) reported that the combined effects of enhanced total transgene expression level and allele-specificity combination in transgenic allele-pyramided *Pm3* wheat lines resulted in improved powdery mildew field resistance without negative pleiotropic effects. All four allele-pyramided lines exhibited strongly enhanced powdery mildew resistance in the field compared to the parental lines.

5.4.2 Mapping of Powdery Mildew Resistance Genes

In 1930, Australian researcher Waterhouse discovered the first powdery mildew (Pm) resistance gene in wheat in the wheat variety "Thew" (Zeller 1973). New powdery mildew resistance genes have been discovered in common wheat and wheat relatives since then. Meanwhile, the inheritance properties of the powdery mildew resistance genes and chromosome positions have been extensively studied (Bhullar et al. 2010a, b; Brunner et al. 2012; Hanusova et al. 1996). Over 91 Pm resistance genes have been identified so far, with 61 loci mapped to them. Apart from these, new genes are continually been searched and described in common wheat and its different relatives (Hao et al. 2015; Li et al. 2017, 2019a, b, c; Tan et al. 2019; Zhang et al. 2017a, b). These genes provide protection for the wheat crop at the seedling stage or at the adult plant stage. However, only a few of them have been widely used in the development of disease-resistant wheat cultivars. For example, Pm8 was introduced from rye in the form of wheat rye 1BL:1RS chromosome translocation. Wheat cultivars such as Kavkaz, Lovrin 13, and Aurora, all having *Pm8* gene have been extensively used as parental lines in wheat improvement programs due to their efficacy against powdery mildew, high yielding ability, and broad genetic base from the time they were first introduced into China in the 1970s. *Pm8* has been incorporated into local wheat genotypes, resulting in the production of a number of commercial wheat cultivars that are locally adapted. Another important Pm gene used in wheat improvement programs is *Pm21*, which is derived from *Haynaldia villosa* L. (Li et al. 2007). With the exception of the fewest, most known Pm genes, especially those derived from closely or distantly related wheat species which have not been used in the wheat breeding programs due to the presence of linkage drag, resulting in decreased agronomic importance. Strong efforts are needed to improve their agronomic scores, increase their yield potential, and eliminate other undesirable traits. As a result, breeders prefer to use Pm genes identified from improved genetic backgrounds with promising agronomic performance. Several *Pm* genes have been identified in Chinese wheat cultivars, such as Yumai 66 (Hu et al. 2008), Zhoumai 22 (Xu et al. 2010), Liangxing 66 (Huang et al. 2012), and Tangmai 4 (Xie et al. 2017). The *Pm* genes in the widely cultivated Jimai 22 (*PmJM22*) and Liangxing 99 (*MlLX99*) wheat cultivars were localized on 2BL chromosome (Yin et al. 2009; Zhao et al. 2013). The *MlLX99* was permanently designated as *Pm52* (McIntosh et al. 2014). A saturated generic linkage map of *Pm52* has recently been established (Wu et al. 2019), which allows the target gene to be precisely detected. *Pm52* was effective against 81% of 123 Bgt isolates from different regions of China (Zou et al. 2017) and 94% of another 49 Bgt isolates from Northern China (Ma et al. 2018).

Various types of mapping populations such as F_2 population, $F_{2:3}$ populations, backcross (BC), recombinant inbreed lines (RILs), near-isogenic lines (NILs), double haploid (DH), and inbred lines (ILs) can be used for mapping purposes. $F_{2:3}$ population is the result of the generation of single-generation F_2 individuals. Like the F_2 populations, they are also of a mortal nature. Neu et al. (2002) developed a population of F_2 to map the *Pm1a* allele of the *Pm1* gene. The *Pm2c* gene was mapped to the F_2 population (Xu et al. 2015). Dong et al. (2020) used the F_2 population to map the *Pm57* gene in *Aegilops searsii*. Genes *Pm59*, *Pm63*, *Pm64*, and *Pm65* have been mapped using populations of F_2 and $F_{2:3}$ (Tan et al. 2018; Li et al. 2019a, b, c; Tan et al. 2019; Zhang et al. 2019). The backcross (BC) population is formed by crossing the F_1 hybrid with one of its parents. They also need less time to generate. BC population has been used to map several powdery mildew resistance genes, such as *Pm4c*, *Pm43*, and *Pm2b* (Hao et al. 2008; He et al. 2009; Ma et al. 2015). Recombinant inbreed lines (RILs) are the result of continuous inbreeding of individual members of the F_2 population until complete homozygosity is achieved. They are immortal in nature and are important for the purposes of QTL mapping. However, they require a number of seasons to develop.

Chhuneja et al. (2012) mapped two powdery mildew resistance genes, *PmTb7A*.2 (new allele of *Pm1*) and *PmTb7A*.1 in *T. boeoticum* acc. *pau5088*, using the RIL population. The *Pm49* gene has also been mapped using the population mapping of the RILs by Piarulli et al. (2012). Hao et al. (2015) used RILs population to map the *Pm54* gene in soft red winter wheat. Similarly, near-isogenic lines (NILs) can also be generated by repeated backcrossing of the F_1 hybrid with the recurrent parent. Such lines may be helpful in tagging genes for powdery mildew resistance, which are generally monogenic. For example, Tao et al. (2000) mapped *Pm6* gene on the chromosome 2BL using NILs population. Nematollahi et al. (2008) successfully used NILs population for mapping of *Pm5d* gene. *Pm4e* gene has also been mapped with NILs mapping population (Ullah et al. 2018).

Mapping of resistance genes facilitates in locating a particular gene on the chromosome. There are a large number of powdery mildew resistance genes in wheat, which have been mapped using different molecular markers. These markers tend to cosegregate with the gene of interest. With the development of markers tightly linked with the gene, we can screen population for marker which ultimately linked to the resistance gene that aids in marker-assisted selection. Already many powdery mildew resistance genes have been labelled with molecular markers. Singrun et al. (2003) found that SSR and AFLP marker, GWM344-null–S13M26–372, was linked to an allele of *Pm1* gene, *Pm1e,* with a genetic distance of 0.9 cM and 0.2 cM, respectively. Ma et al. (2014) used F_2 population for tagging of Pm4a powdery mildew resistance gene using SSR markers and reported that *Xgwm356*, SSR marker, was closely linked to the gene and can be used for marker-assisted selection. Nematollahi et al. (2008) developed NILs population for screening of markers linked to the allele of *Pm5* gene, *Pm5d,* and observed that *Xgwm611* and *Xgwm577* were at genetic distance of 2.1 cM and 2.0 cM from gene, respectively. Luo et al. (2009) reported that the close flanking SSR marker, *Xgwm297,* with genetic distance of 0.4 cM will enable marker-assisted transfer of *Pm40* gene into wheat breeding populations. The closely linked molecular marker, BF146221, congregated with *Pm42* gene (Hua et al. 2009). *Pm6* was found to be closely linked with STS markers; *CINAU127*, distally at 1.1 cM, and *CINAU123*, proximally at 0.1 cM distance (Qin et al. 2011). The Pm46 gene was located on the 5DS chromosome and flanked by SSR markers *Xgwm205* and *Xcfd81* at 18.9 cM apart (Gao et al. 2012). *MlIW172* resistance gene was found closely linked to the *Xpsr680*

RFLP probe derived from the *Xmag2185* STS marker and the BE405531 and BE637476 EST markers (Ouyang et al. 2014).

Bulked segregant analysis showed that multiple simple sequence repeat (SSR) markers, *Xgwm499* and *Xwmc759,* flanked the *Pm53* gene with 0.7 cM proximally (Petersen et al. 2015). Tan et al. (2018) developed STS markers – *Xmag1759* and *Xmag1714* – that are tightly linked to *Pm59* gene with a genetic distance of 0.4 cM on the distal side and 5.7 cM on the proximal side. *Pm61* was positioned in a 0.71 cM genetic interval and can also be observed in a high-throughput scale by the *Xicscx497* and *Xicsx538* SSR markers (Hu et al. 2019). Recently, *Pm57* was physically mapped on the long arm of $2S^{s}$#1chromosome of *Aegilops searsii* and was flanked by markers *X67593* and *X62492* (Dong et al. 2020). These markers will allow the efficient utilization of genes to the wheat breeding program, thus contributing to its genetic diversity.

5.5 Challenges

The current populace of 7.6 billion individuals on the planet is assessed to rise to 10 billion by 2050. With quick populace development, the world has grown exponentially in cities and the extent of nourishment producers for food consumers has dropped drastically. This has put weight on food generation around the world, but escalated, proficient agricultural production has met these needs. There is, however, a genuine concern that the anticipated increment in demand for planted crops up to 70% over the following 30 to 40 years cannot be met with expanded efficiency utilizing current crop varieties and cultivating practices.

Moreover, the Earth's climate has undergone major changes since the industrial revolution and is anticipated to change even more in the near future (Pachauri et al. 2014). For illustration, the worldwide mean surface air temperature has expanded by 0.74 ± 0.18 °C over a 100-year period (1906–2005) and is anticipated to rise by an extra 1.0–3.7 °C by the end of the twenty-first century, owing to the aggregation of nursery gasses (Anderson et al. 2016; Deryng et al. 2014; Huang et al. 2017; Jiang and Fu 2012; Pachauri et al. 2014; Solomon et al. 2007). Climate change too has been applying a noteworthy effect on the event and epidemics of crop pests and infections (Coakley et al. 1999; Fischer et al. 1995; Goudriaan and Zadoks 1995; Rosenzweig and Parry 1994; Rosenzweig et al. 2001).

In this context, wheat powdery mildew (caused by *Blumeria graminis* f. sp. *tritici*) has ended up becoming one of the foremost vital wheat diseases due to changing climate conditions, vulnerability of developed varieties, extensive irrigation, and utilization of nitrogen fertilizers (Cao et al. 2010; Cao et al. 2015; Shen et al. 2015). The frequency dispersion of *B. graminis* f. sp. *tritici* segregates with distinctive temperature sensitivities shows that the pathogen populaces have been impacted by selection pressure from changing temperature. In this way, given the seriousness of wheat powdery mildew, the association of pathogens and climate alterations, and current understanding of the conditions beneath which wheat powdery mildew flourishes, it is imperative to explain the impacts of climate alterations on plagues of wheat powdery mildew. Plant growth at higher nitrogen accessibility may result in expanded disease severity (Mitchell et al. 2003) since the utilization of nitrogen fertilizer may result in a denser canopy and a more sticky microclimate (Bremner 1995). Moreover, this issue ought to be considered to decide the relationship between wheat powdery mildew plagues and changing climate under the biological systems utilizing high nitrogen.

Biodiversity preservation is another major challenge confronting cereal breeders within the twenty-first century. High yield and other desirable agronomic characteristics are the main needs of advanced wheat breeding programs, which is frequently related to a chance of losing hereditary differences for disease resistance. In conventional farming, agriculturists plant a variety of crops that ordinarily have an expansive supply of interesting genotypes. The large-scale development of high yielding varieties and their monoculture has driven an undesirable misfortune in crop hereditary diversity. Conventional crops have the most elevated gene diversity and as they wane, those genes disappear. These hereditary diversity losses can be seen all over the world in areas that actualized green revolution farming strategies. Modern bread wheat (*Triticum aestivum* L.) varieties ought to have high yields, high protein substance, as well as high resistance to biotic and abiotic stresses. High-yielding varieties of bread wheat seem to account for up to 90% of wheat production around the world within the twenty-first century. In any case, only a restricted number of local varieties, a number of which are closely interrelated, can be utilized as breeding materials, which limits down the diversity of gene pool of bread wheat. For this reason, closely related taxa of T. aestivum are progressively utilized for advancement of new varieties with alluring agronomic characteristics, high dietary esteem, handling quality, as well as resistance to the economically critical parasitic pathogens. Hexaploid spelt (*Triticum spelta* L.) one of the closely related taxa, for all intents and purposes, having no crossing obstructions with bread wheat, which empowers the generation of fertile and steady hybrids characterized by superior grain quality and resistance to pathogens compared to bread wheat.

Two primary avenues for expanding crop efficiency are, namely, the arrangement of genetically predominant crop varieties and other, by selection of better management practices, which ought to be tended in parallel to provide a step change in efficiency comparative to what was accomplished through green revolution. Green revolution depicts the colossal increment of grain yield related with improved genetics and application of plant protection chemicals and mineral fertilizers. Whereas it took nearly 10,000 years for people to create 1 billion tons of grain universally, the green revolution led to multiplying of that amount in just 40 years between 1960 and 2000. The appearance of smaller, more stable varieties with a higher gather record went accompanied by a few positive impacts, counting a progressed allotment of supplements and assimilates to the grains and a reduction in leftover plant biomass.

Intercropping is supplanted by monocropping, a wide difference of species is replaced by a small number of commercial assortments. As a result, the awesome genetic diversity inside the same crop species is replaced by a narrow hereditary range of fiscally lucrative varieties. The net effect of these and other practices has been an enormous uprooting of innate seed varieties, such that within the case of most major crops now, the larger part of indigenous cultivars are not developed. Hence, due to a limited genetic base of the current Indian wheats with regard to the resistance range (most of the high-yielding wheat assortments infer their resistance to rusts and fine buildup from the 1BL/1RS translocation) and intensive cultivation practices, there has been an increment in the frequency of rusts and more prominent severity of powdery mildew and other already minor maladies. Hence, green revolution brought modern challenges to sustain its growth under unused challenges of genetic defenselessness to maladies and disease management with environmental contemplations.

5.5.1 Linkage Drag Associated with Introgression of Exotic Resistance Alleles Using Conventional Breeding

Routine breeding is still the foundation within the trim enhancement pipeline. It is conducted by crossing plants with characteristics of intrigued and selecting the offsprings with the ideal combination of characteristics. In any case, linkage drag leading to the presentation of outside chromosomal segments containing resistance can come with pleiotropic impacts since harmful qualities related to poor agronomic performance in yield or quality will also be introgressed at the side the quality of interest. Yield penalties of resistance in wheat have been detailed for Pch1 (Johnson 1992; Groos et al. 2003) and Pm16 (Chen et al. 2005). A chromosome fragment from *Aegilops ventricosa* has carried both the eyespot resistance quality Pch1 and yield-reducing qualities in wheat (Doussinault et al. 1983; Groos et al. 2003). This potential "linkage drag" incredibly puts confinements on the coordinated use of *Pm* qualities in breeding programs.

In addition, one of the major bottlenecks of plant breeding is the time it takes to create a progressed trim assortment. In this case, routine breeding strategies take numerous eras and time (ordinarily 6 years for conventional breeding of self-pollinating crops) to assess phenotypes and get the target recombination of genes, which is clearly time devouring (Cowling 2013). Indeed so, significant benefactor DNA material can still be found alongside genes of interest in eras after different backcrosses (Young and Tanksley 1989). The issue of linkage drag is exacerbated in breeding self-pollinating crops, where levels of linkage disequilibrium were found to be 200 times higher than in out-crossing crops (Rostoks et al. 2006). Additionally, the rate at which foreign segments recombine with wheat chromosomes is lower than when a wheat homoeologous partner is utilized. For this reason, confinement of resistance genes by routine map-based cloning has run into more challenges. Such challenge in hereditary illustration has been illustrated in cloning of Pm21 on the 6VS arm, beginning from the Triticeae grass *D. villosum* (Chen et al. 1995). Recombination hindrance of remote chromosome 6VS through a map-based cloning technique was not attainable for Pm21 (Qi et al. 1998). More noteworthy exactness in mapping the physical area of resistance genes is undoubtedly vital for distinguishing candidate genes, and the position of embedded alien segments within the wheat genome too accounts for effective improvement of the crop (Dundas et al. 2007).

The improvement of cytogenetic stocks made a difference to find Pm21 and recognized a serine/threonine kinase gene Stpk-V upgrading powdery mildew resistance (Cao et al. 2011). However, it was dubious in case Stpk-V gene that whether a candidate gene or set of genes at the Pm21 locus is responsible for developing resistance. This speculation was upheld by the proven fact that Stpk-V silencing did not totally compromise resistance of Pm21 (Cao et al. 2011). Later work advance substantiates the theory where two commonplace NLR qualities, DvRGA2 (He et al. 2018) and NLR1-V (Xing et al. 2018), were found as candidates for Pm21 and are likely allelic. Subsequently, plant breeders and analysts around the world are creating unused advances and approaches to assist speed up of the productivity of crop breeding.

5.5.2 Fungicide Resistance

Cereal mildews have an inherently high resistance risk because of their remarkable ability to adapt to fungicide treatments. Currently, resistance in mildew to quinone outside inhibitors (QoIs) is high across Northern and Western Europe. Following an initial shift toward reduced sensitivity, the sensitivity pattern to the morpholines and DMIs has remained stable for several years. Isolates with reduced sensitivity to quinoxyfen have been found in Europe with reports of reduced performance. Isolates with reduced sensitivity to metrafenone have been found but field performance remained good. Good resistance management strategies should be followed by applying fungicide before the disease becomes severe, rotating fungicides, and not using more than two sprays of any product per season. But the initial genetic changes (or “gateway” mutations) in wheat powdery mildew strains will always be a threat leading to fungicide resistance issues in powdery mildew management.

5.5.3 Fast Jump: Expansion of the Host Range Due to Pathogen Diversity

Climate change is a generic term that explains the recent and forecasted change in multiple environmental factors. Most of them, including atmospheric CO_2 concentration, temperature, and the frequency and amount of precipitation, affect plant growth. Beyond the temperature optimum, which is very crop and variety specific, higher temperatures result in heat stress, which is considered a major cause of wheat yield loss in developing countries. It has been estimated that each °C increase leads to a decrease in global wheat production by 6%. Increasing temperature can also indirectly affect crop yields due to an increased occurrence of pests and diseases.

5.6 Prospects for Broadening the Genetic Basis of Host Resistance

Need to feed a rapidly growing population in the face of visibly changing climate has raised concerns for global food security. In times of rapid population growth and visibly changing climate, the rate of improvement of genetic yield potential and resistance against fast evolving plant pathogens has to be increased beyond current rate achieved by the ongoing breeding programs to protect global food security. While plant breeding has been very successful and has delivered today's highly productive crop varieties, the rate of genetic improvement must double to meet the estimated future demands. For this, a set of new approaches are needed to accelerate the crop breeding process.

In a broader sense, any breeding program can be broadly classified into three main processes: (1) the creation of new genetic variation, (2) the selection of best individuals based on set objective of improvement, and (3) the evaluation, multiplication, and release of improved crop varieties. The conventional way of creating new genetic variation is to attempt targeted crossing between selected individuals to create desirable segregants and further to identify genetically superior individuals from typically large populations of genotypes. Longer generation times taken in conventional breeding represent a major bottleneck for crop breeding, apart from multiple breeding cycles, especially due to time-consuming line fixation. For self-pollinating crops (i.e., wheat), usually six to eight generations are expected for genetically heterogeneous breeding lines to reach fixation (Lenaerts et al. 2019). Further, after release of a variety, the adoption of poor or suboptimal management practices in farmers' fields results in a yield "gap," where the potential yields of varieties are not realized. Therefore, closing the yield gap between potential and realized yields is considered a challenging and high-priority goal for enhancing productivity and global food security.

For most important crop species, modern selection strategies have been developed that incorporate genome information based on next-generation DNA sequencing technologies in the breeding process. Modern plant breeding programs have become highly multidisciplinary involving genetics, biochemistry, physiology, bioinformatics, molecular biology, statistics, agronomy, and economics as well. Advances in DNA sequencing technologies have revolutionized plant breeding research, opening up the "genomics era" of crop improvement. Very cost-efficient genotyping platforms to "DNA fingerprint" plants have been developed and whole-genome reference DNA sequences are available for most important crop species. Single nucleotide polymorphisms (SNPs) have become the markers of choice because of being ubiquitous in plant genomes and very easy and cost-efficient to score. It has, therefore, become common practice in modern crop breeding to genotype large populations of plants with several thousands of markers on a routine basis. Whole-genome sequencing data are becoming increasingly available. Large amounts of genotype data are being increasingly used for various purposes using the latest statistical genetics approaches.

5.6.1 Utilizing Exotic Sources for Resistance

High yield and other desirable agronomic traits are the most important priorities of recent wheat breeding programs, which are often related to a risk of losing genetic diversity for disease resistance. Wheat relatives possess untapped diversity for mildew resistance. In this context, interspecific hybridization for introgressing disease resistance genes from wild distant relatives is effective for breeding more resilient cultivars. Among close and wild relatives of *Triticum aestivum*, rye and *Dasypyrum villosum*, respectively, are used for transferring a spread of resistance genes against mildew and rust fungi (Graybosch 2001; Chen et al. 2013; Li et al. 2018). Genes for resistance to mildew (Pm8 and Pm17), as an example, and rust (Sr31, Lr26, and Yr9) on chromosome 1RS of "Petkus" rye are successfully introduced into commercial wheat cultivars worldwide (Jiang et al. 1994; Kim et al. 2004). For *Triticum aestivum*, wild wheat, one among the progenitor species, is additionally an upscale donor of diversity of resistance to varied diseases and may be exploited for trait improvement (Huang et al. 2016). Wild species and primitive forms including wild wheat are the source of the many confirmed Pm genes. Incorporating Pm genes from wild sources into commercial cultivars has been made possible as wild wheat is crossable with both hexaploid (*Triticum aestivum*) and tetraploid durum (Rong et al. 2000; Elkot et al. 2015). Easy crossability of untamed emmer with both hexaploid *Triticum aestivum* and tetraploid durum has made it possible to include Pm genes into commercial cultivars (Rong et al. 2000; Elkot et al. 2015). On the opposite hand, landraces of bread wheat are genetically more polymorphic sources of disease resistance thanks to cultivation for thousands of years under natural environments (Talas et al. 2011; Li et al. 2016), and are rich reservoirs of adaptive traits to abiotic stressors (Reynolds et al. 2007). Compared to distant relatives, landraces are ready for direct crossing of interesting traits into new cultivars. A group of wheat landraces have exhibited highly significant resistance to mildew, formally designated as Pm2c (Xu et al. 2015), Pm3b (Yahiaoui et al. 2004), Pm5d (Hsam et al. 2001), Pm5e (Huang and Roder 2003), Pm24a (Huang et al. 2000), Pm24b (Xue et al. 2012), Pm47 (Xiao et al. 2013), Pm59 (Tan et al. 2018), Pm61 (Sun et al. 2018), Pm63 (Tan et al. 2019), and PmQ (Li et al. 2020). However, PmQ and Pm63 isolated from two different landraces, from Iran and China, are found to be located during a similar genomic region, in order that they could also be allelic. Among others, pyramiding multiple resistance genes into local cultivars is an efficient strategy to extend the sturdiness of mildew resistance. Identification of latest sources of resistance to diversify the resistance base of existing cultivars in wheat is often achieved expeditiously within the north-western Himalayan regions like states of Himachal Pradesh, where the second wheat crop is often taken in summer within the dry temperate zone. There is a requirement to specialize in utilization of diverse sources of slow mildewing resistance to Bgt. Clues might be taken from genetic analyses of durable resistance in *Puccinia graminis* diseases which indicate that effective disease control is often achieved by combining three to five minor, slow rusting genes during a single cultivar. Such resistance is predicted to supply sufficient protection to farmers' crop against all pathotypes over an extended period. Efforts will also be needed to use molecular markers in order to identify chromosomal regions containing genes for slow mildewing resistance present within the diverse sources.

5.6.2 Marker-Assisted Selection and Precision Phenotyping

Molecular marker may be a fragment of DNA that is readily detected and whose inheritance is often monitored easily. They are located near a gene or gene of interest and are used to identify particular locations where the sequences differ among varieties. They have been successfully used to map mildew resistance genes in wheat. The identification of molecular markers linked to resistance genes could facilitate marker-assisted selection. A perfect DNA marker should generate polymorphisms indicating slight changes within the genome of two different genotypes. It should be codominant and have multiple alleles to supply adequate resolution of genetic differences among individuals/lines. As many agronomically important traits are polygenic/quantitative in nature, like yield and disease resistance, QTL mapping is used to get marker-trait association (Collard and Mackill 2008). Valuable markers are then utilized in marker-assisted breeding to screen individuals. MAS shortens the breeding cycle and has many advantages in selecting disease-resistant plants compared to phenotyping (Tanweer et al. 2015). With QTL-MAS, many genes and alleles are often introduced to commercially favored cultivars. MAS also can be combined with genomic selection (Nakaya and Isobe 2012) to form the breeding cycle simpler and efficient. Unlike traditional MAS, which mainly selects for QTLs with modest-to-large effects, an upgraded sort of MAS named genomic selection captures all minor-effect QTLs also, identifying individuals with high genomic estimated breeding value (GEBV) for the chosen traits (Desta and Ortiz 2014). It relies on genomic prediction of the likelihood of every individual to possess a superior phenotype; therefore, GEBV-based selection reduces the number of generations required (Bassi et al. 2016). Accurate, precise phenotyping plays an increasingly pivotal role for the choice of resistant genotypes and, more generally, for a meaningful dissection of the quantitative genetic landscape that underlines the resistance pattern. Evaluation of quantitative resistance requires reliable phenotyping data, and accurate genotype-phenotype association is critical for candidate gene identification. However, disease estimation by commonly adopted visual scoring is extremely subjective and error prone (Poland and Nelson 2011), and within the case of a large-scale screening, this method greatly limits efficiency and accuracy of phenotyping. MAS is essentially conducted alongside linkage mapping in family-based populations, genome-wide association mapping in natural diversity populations, and joint linkage association mapping using both sorts of populations of these mapping methods to process which requires both genotypic and phenotypic data. Obtaining reliable phenotype data is pivotal for identifying true trait-associated markers. Within the case of mildew APR, the phenotype is usually disease severity, measured either as disease index (i.e., 0–9 scale) or as percentage disease at a selected adult stage. However, the resistance response might change as plants mature, which is seen in some powdery mildewed cereals including wheat (Carver and Adaigbe 1990; Duggal et al. 2000). This was also observed in QTL mapping of mildew resistance in mungbean, during which a QTL was found for resistance effective 85 days after sowing, while no resistance was expressed 20 days earlier (Young et al. 1993). Multiyear and environment field trials are necessary for QTL detection because it is common for a QTL identified during one year-environment scenario to not appear in another year-environment combination.

For durable resistance breeding, resistance QTLs with consistent performance over several years, environments, and plant growth would be more valuable. Given the character of the phenotypic expression of slow mildewing, the timing of scoring the phenotypes is vital for assessing the extent of resistance. Disease severity at one time point is not the sole component concerning resistance; the length of the latent period, survival percentage, and area under the disease progress curve (AUDPC) even have potential in discovery of resistance loci through these traits, very probably controlled by overlapping QTLs (Wang et al. 1994; Muranty et al. 2009; Chung et al. 2010). Inspired by this, future QTL mapping could address more of those resistance-relevant components. QTL mapping clarifies significant markers that are beyond an assigned threshold, mentioned as logarithm of odds (LOD) in linkage mapping and p value in genome-wide association studies. However, not every QTL exceeding these criteria may be a true candidate region because it could be a false positive. In linkage mapping, QTLs of mildew resistance in wheat always function with additive effects, but in some mapping studies epistatic interactions between these QTLs also appear (Goldringer et al. 1997). This confounds evaluation of QTLs because the existence of epistasis can mask latent genetic variation for quantitative traits (Mackay 2014). Development of high-throughput phenotyping technologies (crop phenomics) provides a useful set of tools for assisting precision breeding (Zhao et al. 2019). Some image-based technologies like fluorescence imaging and spectral imaging have already been demonstrated as promising diagnostic tools in detecting wheat mildew (Yuan et al. 2012; Zhang et al. 2012; Ajigboye et al. 2016).

5.6.3 Advances in High-Throughput Genotyping Technologies and Genomics

Development and application of molecular markers in crop breeding are impactful in parental selection, genetic diversity estimation, and reducing linkage drag and, thus, of paramount importance in genetic mapping and gene discovery (Rasheed et al. 2017). The genome-wide molecular markers derived from modern technologies like array- and sequencing-based genotyping have overcome the scarcity of genetic markers, and facilitated the identification of resistance genes or QTLs in mapping experiments. For instance, array-based SNP platforms improve the marker coverage and mapping resolution, and may more efficiently and accurately target R genes or define genomic regions related to quantitative traits. SNPs are important contributors to phenotypic variation (Saxena et al. 2014), and therefore, the use of a high-throughput SNP array in wheat is rapid, where a series of fixed SNP arrays were produced in wheat from 9 K to 820 K (Cavanagh et al. 2013; Wang et al. 2014; Winfield et al. 2016; Allen et al. 2017). Alternatively, an ever-increasing throughput of next-generation sequencing (NGS) technologies is often wont to assess genome-wide diversity. It is possible to rapidly identify causal variants during a single step by using NGS (Schneeberger 2014). Embedded in genetic mappings, high-density SNP genotyping arrays and NGS have helped a substantial number of studies to molecularly detect mildew resistance genes/QTLs during a wheat panel (Liu et al. 2017a, b; Chao et al. 2019).

In spite of this, the wheat genome (~17Gb in size) remains too enormous to figure out using NGS processing especially as it is just too cumbersome due to massive size of wheat genome. To deal with this difficulty, different approaches are developed to scale back such complexity in large-genome species like wheat. Rapid isolation of resistance in wheat has been facilitated greatly with the advances in DNA sequencing and bioinformatics technologies. Exome capture and sequencing is one such approach, which greatly reduces sequencing volume and costs, while giving detailed coverage of gene coding regions or sufficient mapping information of a genomic interval containing causal gene (Mo et al. 2018). Exome capture assays are used for identification of candidate genes for plant height and resistance to leaf and yellow rust in wheat mutants (Hussain et al. 2018; Mo et al. 2018). With the prior map information of the targeted gene and isolation of individual chromosomes, targeted chromosome-based cloning via long-range assembly (TACCA) is often used. The success of this approach has been demonstrated by the isolation of Lr22a, a wheat leaf rust R gene (Thind et al. 2017). Construction of high-density maps is often bypassed by some novel isolation techniques that use mutational genomics for resistance gene cloning. Combined with chemical mutagenesis, another fine mapping-independent strategy employing exome capture and sequencing was developed to focus on NLR-type resistance genes for cloning (MutRenSeq) (Steuernagel et al. 2016). This group of researchers applied MutRenSeq for isolation of two R genes (Sr22 and Sr45) that confer stem rust resistance in wheat. More recently, a speed cloning approach using high-throughput DNA sequencing (AgRenSeq) for NLR gene enrichment was reported to spot and isolate four wheat stem rust R genes from the wheat wild progenitor *Aegilops tauschii* (Arora et al. 2019), the D genome donor of bread or hexaploid wheat.

These state-of-the art genomic technologies effectively catch up on the reduced recombination during introgression of foreign sources of disease resistance to wheat (Wulff and Moscou 2014), paving the way for fast-track identification of resistance loci and, therefore, the utilization of crop's wild relatives. The entire reference genome of hexaploid wheat (Chinese Spring) recently became publicly available (Appels et al. 2018), providing vast potential for discovery of untapped genetic resources by enabling the alignment of genetic and physical maps. Realizing the importance of genome diversity in wheat for crop improvement, ongoing sequencing efforts have also been applied to different wheat cultivar. The so-called wheat pangenome allows identification of novel genes and alleles absent within the single reference accession (Sanchez-Martin and Keller 2019). Available pangenomes of the wild relatives of wheat is of paramount relevance in wheat resistance breeding, which facilitates identifying orthologues for the rationale that wild relative-derived R genes are usually suppressed by their orthologues in domesticated wheat (Sanchez-Martin and Keller 2019). The arrival of NGS technologies has begun to provide insights into genetic diversity for optimizing crop improvement, and also set in motion, the new landscape of pathogen study, pathogenomics, an emerging genomics era. Field pathogenomics has revolutionized crop pathogen surveillance and diagnostics, and by increasing understanding of pathogen biology, population structure, and pathogenesis offers the prospect to predict emerging epidemics (Hubbard et al. 2015; Möller and Stukenbrock 2017). This approach allows researchers to get sequencing data directly from field samples of diseased plant tissues. Moreover, it can trace pathogen evolution to tell development of suitable wheat lines with both strong and long-lasting resistance.

5.6.4 Potential of New Breeding Technologies and Transgenic Approaches

Over the past decades, a vast number of technologies have emerged, which will accelerate plant breeding efforts. Among them, genomic selection, as an example, has emerged to be a really promising modern selection strategy that comes with genome-wide DNA marker information, during which statistical models or machine learning algorithms are deployed to link genomic polymorphisms to phenotypic variation. This enables breeders to predict genotype performance as soon as DNA marker profiles are often generated (i.e., at seedling stage) employing a genomic estimated breeding value (GEBV) for every genotype. Using this approach, the time until selection decisions are being made is significantly decreased, which results in increased genetic gain per unit of your time. Till date, genomic selection has led to tremendous increases in genetic gain in animal breeding with great promises for crop improvement also. Among others, methodologies like gene editing technology are fast evolving and protocols are refined for many major crop species. In CRISPR gene editing systems, guide RNA directs the Cas9 enzyme to the target DNA site and cuts the DNA. This will be wont to activate or deactivate alleles of a target gene to reinforce plant performance, for example, through improving disease resistance or drought tolerance.Despite the promise of gene editing and powerful support from the scientific literature regarding safety and sustainability, many countries have employed strict legal restrictions favoring rejection of genetically modified food. On the other hand, a really widely used and accepted breeding method is mutation breeding, which uses chemicals or radiation to induce random mutations throughout the genome rather than genetically engineered (targeted) mutation. This is often why the bulk of the plant science community contends that mutations induced using genome editing, where no foreign DNA is introduced, should be considered a non-GM tool.

5.6.5 Genetic Engineering

Plant transformation has the advantage of having the ability to interrupt interspecific crossing barriers and provides an alternative to standard breeding methods for disease resistance that potentially can expand the available gene pool. However, the procedure is restricted to genes already cloned; extensive testing is required to make sure stability and heritability of the transgene and transformation can sometimes have a negative effect on agronomic performance (Campbell et al. 2002). Wheat, like other cereals, presents the extra challenge of not being amenable to Agrobacterium-mediated transformation (Wu et al. 2003). In comparison to biolistic procedures, Agrobacterium transformation has the benefits of providing a more precise insertion of the transgene, greater stability, and lower copy number (Meyer and Giroux 2007). Significant progress has been made in improving transformation procedures in wheat, both on biolistics (Srivastava et al. 1999) and Agrobacterium-mediated gene transfer (Khanna and Daggard 2003; Wu et al. 2003). Particle bombardment was used successfully to get transgenic wheat expressing a barley seed class II chitinase (Bliffeld et al. 1999) and a tobacco β–1,3-glucanase gene was transferred to wheat seedlings via Agrobacterium transformation (Zhao et al. 2006). In both cases, increased resistance to mildew was reported. Incorporating monogenic resistance to mildew by means of gene splicing faces an equivalent challenge as conventional breeding regarding resistance durability. Transforming wheat with several antifungal proteins to enhance mildew resistance was attempted by Oldach et al. (2001). The researchers used three proteins: the antifungal protein AgAFP from *Aspergillus giganteus*, a barley class II chitinase, and sort I ribosome inactivating protein (RIP). They found that simultaneous expression of the AgAFP and, therefore, the barley chitinase enhanced mildew resistance quantitatively, whereas the RIP gene had no effect on this disease. An alternate strategy being explored is that the use of gene splicing to control defense signaling pathways so as to activate multiple defense genes and induce the systemic acquired resistance (SAR) (Stuiver and Custers 2001). The NPR1 gene from Arabidopsis, a key regulator of SAR, was wont to engineer wheat plants with improved resistance to Fusarium blight (caused by *Gibberella zeae*) (Makandar et al. 2006). Genetic modification (GM) and genome editing are often utilized to expand the genetic tools within the hands of researchers to enhance disease resistance. GM delivers genetic improvement for wheat breeding because it enables faster transfer of resistance genes from another species compared to standard crossing and overcomes sexual barriers. Transgenic wheat lines expressing antifungal barley seed class II chitinase and exhibiting enhanced resistance against mildew (Bliffeld et al. 1999) are samples of the effectiveness of GM. Polyploid nature of *Triticum aestivum* essentially makes it challenging to get stable inheritance of traits developed by DNA editing tools to induce mutations. The advances in forward screening make it feasible. Genome editing via sequence-specific nucleases (SSN) with introduction of transcription activator-like effector nuclease (TALENs) together simultaneously edited three MLO homoeoalleles within the same wheat individual; resistance during this triple mutant is complete and heritable (Wang et al. 2014). However, TaMlo modifications caused leaf chlorosis in plants. Limitations of the mlo mutant include the common observation of coupling to undesirable traits for instance, spontaneous leaf decay, which has been a symbol of yield penalty, the potential of enhancing sensitivity to another pathogens, and also as reduced plant size (Jarosch et al. 1999; Zheng et al. 2013; McGrann et al. 2014; Acevedo-Garcia et al. 2017). The good potential of the CRISPR/Cas9 technique for improving disease resistance makes it perhaps the best known and most generally adopted genome editing tool (Hilscher et al. 2017). CRISPR/Cas9 is demonstrated to achieve success in enhancing mildew resistance of wheat (Wang et al. 2014), tomato (Nekrasov et al. 2017), and rice blast resistance (Wang et al. 2016). It had been adapted from a naturally occuring genome editing system in bacteria, through single-guide (sg) RNA-mediated DNA mutation to manipulate and encode the new traits in plants (Knott and Doudna 2018). CRISPR/Cas9 technology does not involve the insertion of a gene from a special organism; rather, it involves gene/genome editing. Evidence of edited plant progeny freed from CRISPR genes indicated a possible strategy for producing nontransgenic crops (Char et al. 2017; Chen et al. 2018). Recently, progress in targeting induced local lesions in genomes (TILLING) technology has been applied in wheat for the assembly of economic powdery mildew-resistant varieties. TILLING combines high-throughput genotyping for mutations with traditional chemical mutagenesis, which is more efficient to spot single nucleotide mutations in regions of interest (McCallum et al. 2000). The orthologue of barley Mlo are created using TILLING, as several combinations of mutant alleles of TaMlo are carried by partially resistant bread wheat lines (Acevedo-Garcia et al. 2017). Hence, there is no evident abnormality in plant growth due to the loss-of-function of TaMlo homoeologues which overcame the disturbance of pleiotropic phenotypes.

5.6.6 Transgenic-Based Resistance

Failure in transgenic plants has often been addressed, like poor or maybe no expression or inheritance of a transgene (Kumar et al. 2016). Also, transgene expression might be suffering from environment. For instance, field conditions are generally more complicated than a controlled environment, and in this sense, more genetic factors might be involved in biological and physiological activities and interact with transgene (Ueda et al. 2006). Moreover, uncontrolled transgene insertion might end in uncertain detrimental effects on plant growth and development. The subject surrounding genetic modification is usually related to concerns about potential hazards from transgenic plants; many countries, especially in Europe, have announced a ban on planting transgenic seeds. Release of strains employing a cisgenic approach is taken into similar risk as to standard breeding because cisgenic plants only have genes from an equivalent species or from a crossable relative (Schouten et al. 2006). It takes a breakthrough from introgression breeding because it directly transfers functional genes without multiple transfer steps that involve linkage of other genes (Jacobsen and Schouten 2007). Further, wheat breeding projects can use cisgenic methods, as wheat and progenitors and such relatives are great sources of resistance genes. Despite the very fact that genome-edited plants are indistinguishable from those formed by natural or induced mutations (e.g., ethyl methanesulfonate) or conventional breeding (Duensing et al. 2018), many countries are still debating whether genome-edited crops should be subject to an equivalent regulation as genetically modified organisms (GMO). The importance of CRISPR/Cas9 as a transgenic approach lies in the need to develop transgenic lines to introduce the CRISPR/Cas9 into the genome of the target plant (Collinge 2018). However, transgenesis-free methods are developed for vegetatively propagated crops and perennials (Danilo et al. 2019). Moreover, methods to efficiently eliminate editing machinery and choose transgene-free CRISPR/Cas9-edited crop plants also are available for dry seeds (Aliaga-Franco et al. 2019). The regulatory requirements for genome-edited crops are currently controversial within the European Union because the European Court of Justice (ECJ) declared products of genome editing as GMOs in 2018 (ECJ 2018). This supported GMO legislation issued in 2001 (Official Journal of the ECU Communities 2001) did not consider CRISPR/Cas9 approaches. Consequently, scientists and breeders in Europe are urgently calling for the GMO ruling to be updated to a product-based evaluation instead of a process-based one (Collinge 2018; Schulman et al. 2019). Several countries outside Europe have excluded genome-edited crops from GMO regulations, like the USA, Argentina, and Japan (Schulman et al. 2019). US market pipeline already has a minimum of 20 genome-edited crops, stated to be exempted from GMO legislation (Schulman et al. 2019). In spite of the differences in regulatory approach, these new breeding technologies are believed to represent a sustainable solution to global agricultural challenges, crucial for reducing pesticides and securing food supply.

5.7 Need for Speed: An Intimidating Priority

Since the green revolution, steady increases in crop productivity have occurred; however, there is concern that yield improvement is beginning to plateau. The current rate of annual yield improvement for major crops ranges between 0.8 and 1.2%, which must be doubled in order to meet the highly increased future demand for plant-based products. In this context, new technology and advances in science offer new opportunities to further improve the efficiency of agriculture, while reducing its negative environmental impact, as well as enrich human diets with more nutritious foods. Without new approaches that help boost productivity of staple crops through genetic improvement, global food security will be severely compromised in the next two to three decades, given the current global consumer behavior. Rapid generation advances or in other terms shortening the fixation stage is an important component for reducing the time required to develop a new variety. "Speed Breeding" developed by Dr. Lee Hickey and colleagues provides a non-GM route to rapidly introgress or pyramid new trait variation. Speed breeding (SB) is an effective approach for rapid generation (Watson et al. 2018). SB creates rapid growth conditions by extending the photoperiod in a controlled-environment growth chamber (Ghosh et al. 2018). This method certainly speeds up the line fixation compared with the process under typical glasshouse conditions. Extended photoperiod and controlled temperature regime can help to achieve up to six generations of spring wheat and durum wheat per year (Watson et al. 2018). Moreover, it can also be combined with genomic selection for accelerating crop improvement.

Most of the modern technologies have been proven to assist in the development of improved crop varieties. However, more efficient breeding strategies that effectively combine these technologies could lead to a step change to achieve rate of genetic gain. Ongoing investment from the public and private sectors is necessary to build and maintain capacity for sustained crop improvement to ensure the development of crops that are capable of feeding the world in the future.

5.8 Integrated Disease Management

Apart from the use of the disease-resistant varieties for any disease, crop monitoring is a key to control spread of powdery mildew. Powdery mildew is more difficult to control once it has established itself in crop canopies, so it is always advisable to monitor crops regularly from early tillering, to detect early symptoms, particularly in susceptible varieties. Powdery mildew severity can be exacerbated by high seeding rates, high nitrogen fertilization levels, and semi-dwarf growth habit. (Last 1954; Tompkins et al. 1992). High nitrogen levels escalate plant height and tillering, reducing the culm strength which leads to extended leaf wetness and increased lodging favorable for disease infection (Shaner and Finney 1977). Disease severity in the following wheat crop may be increased in the subsequent crops due to residual nitrogen from the previous wheat crop, which received high rates of nitrogen concentrations, and from legumes that contain nitrogen (Parmentier and Rixhon 1973). Volunteer plants can serve as inoculum source in reduced tillage systems. Potassium deficiency can make crops more vulnerable to infection in potassium-deficient soils but its application beyond need will not reduce disease risk. Hence, improper fertilization levels increase the susceptibility of the crop.

In winter barley, the use of cultivar mixtures to slow a powdery mildew outbreak has been studied (Wolfe 1984). The expected benefits include slowing the epidemic progression, reducing or eliminating the need for foliar fungicides, and thus, reducing the pathogen's ability toward fungicide resistance. Deploying greater number of resistance genes in both spring and winter wheat aims to diversify the population of *B. graminis* f. sp. *tritici,* while mixtures of cultivars containing different resistance genes slowed the progress of the powdery mildew epidemic and improved yield by 5% (Stuke and Fehrmann 1988). Cultivar mixtures have been used on a small scale despite being shown to be useful in many wheat-pathogen systems. The maturities of the cultivars in the mixture must be identical, and the end use must be considered, especially if the crop is to be sold through traditional grain marketing channels.

Powdery mildew infection can be reduced with seed dressing and in-furrow fungicides that are approved for the control of other wheat leaf diseases, however, they are not registered for this use. Young plants are the most vulnerable to the powdery mildew, so minimizing the risk of early disease onset can be helpful in high-risk situations. Currently, no seed dressings or in-furrow fungicides for powdery mildew in wheat have been approved and scanty information is available regarding the integrated disease management approach, but some fungicides have been approved for powdery mildew in barley, including flutiafol in-furrow and fluquinconazole as seed dressing (Department of Primary industries and Regional Development 2020).

Applying registered fungicides can help limit infection in the upper canopy and heads, and is recommended in the more vulnerable varieties. It should be noted, however, that yield increases from a single fungicide have ranged from 0 to 25% in trials, with an average of about 10% (Department of Primary industries and Regional Development 2020). If the disease symptoms return after 2–3 weeks and the conditions remain optimal, a second fungicide application may be required. Early season infection development is regulated by seed-applied systemic fungicides, particularly in winter wheat. Excess tillering caused by mildew infection early in the season was reduced by triadimenol seed treatment, which led to a higher grain yield later in the season, particularly when high temperatures during grain filling reduced the severity of disease (Everts and Leath 1992; Frank and Ayers 1986; Leath and Bowen 1989). Difenoconazole also has systemic activity against powdery mildew. These fungicides have a wide spectrum of activity and may be economical seed treatments when they also contribute to reduction in smuts and other foliar pathogens (Leath and Bowen 1989). Powdery mildew is also treated with difenoconazole, which has systemic activity. These fungicides have a broad range of application and can be cost-effective crop treatments if they also help to reduce smuts and other foliar pathogens (Leath and Bowen 1989).

At present most control measures are based on the use of fungicides at the preflowering stage and in order to find new eco-compatible control methods against wheat powdery mildew, the biocontrol agents (BCAs) like yeasts *Rhodotorula glutinis* (isolate LS11) and *Cryptococcus laurentii* (isolate LS28) and the yeast-like fungus *Aureobasidium pullulans* (isolate LS30) were applied alone or in combination with a low dosage of common fungicides or with natural adjuvants. BCAs added in conjunction with certain adjuvants (i.e., calcium citrate, calcium chloride, calcium propionate, soybean oil, and humic acid) as well as a low dose of fungicides provided the best protection against powdery mildew. Furthermore, leaves treated with BCAs plus mineral salts had the highest amounts of antagonist population (De Curtis et al. 2007).

To prevent the development of fungicide resistance, wherever possible, fungicide mixtures containing several modes of action, such as cyproconazole and azoxystrobin, epoxiconazole and azoxystrobin, and epoxiconazole and pyraclostrobin, should be used. If environmental conditions are conducive to persistence, the first appearance of symptoms should be taken seriously and disease control practices must be implemented as soon as possible. Moreover, it is best to stop using the same fungicide or mode of action, such as demethylation inhibitor (DMI) fungicides, after the previous use. Rotation of the wheat crops with nonhost crops such as canola, barley, or legumes should be frequently practiced. The severity of powdery mildew can be influenced by fertilizer use. Plants become more vulnerable to increased nitrogen fertilization, and dense crop canopies favor epidemic growth. Such crops would necessitate more intensive disease control and management. As a result, managing nitrogen application is critical for reducing the incidence of powdery mildew.

An integrated disease management system should be used with genetic resistance as the cornerstone of the program. Cultural management, including proper management of nitrogen fertilization, is essential to minimize risk of crop damage from powdery mildew. Rotate wheat crops with nonhost crops such as canola, barley, or legumes. Fungicides should be used in conjunction with a disease monitoring system employed from planting through the flowering stage of growth to estimate economic return.

5.9 Concluding Remarks

Molecular genetic research into various resistance forms for wheat powdery mildew is still ongoing. Exploration of underlying gene functions and interactions will be crucial in the future to achieve resilient and high levels of resistance. To diversify their resistance base, more focus will have to be placed on incorporating an array of resistance genes/QTLs into wheat cultivars. Wheat, as a polyploid, has a diverse gene pool that serves a variety of disease resistance sources for broadening the genetic base for powdery mildew resistance. Improvements in genetic techniques could speed up the detection and characterization of novel resistance genes. Current and upcoming methods and developments, including recent gene isolation techniques, would significantly accelerate the excavation of so-called "alien genes" (from cultivated or wild relatives). In plant pathogens, comparative genomics and population genomics provide new and effective ways to detect ongoing and past hybridization (Menardo et al. 2017a, b; Stukenbrock et al. 2012). Experiments on the genetics of reproductive barriers in model ascomycetes have also shed light on the genetics of these barriers (Dettman et al. 2007; Turner et al. 2011). Given the expansion of powdery mildew's host range, a better understanding of the underlying genetics of reproductive barriers and self- versus non–self-identification between species of fungal plant pathogens could help predict hybridization events in various agroecosystems. Therefore, there is a need to efficiently explore modern technologies to boost crop improvement in the face of more challenging production conditions, genetic barriers in alien introgression, and expanding host range of powdery mildew fungus in future. Examining the vast literature, great prospects could be foreseen with the advancements in the molecular diagnostic techniques for pathogen identification, cultivar development, artificial intelligence algorithms, and speed breeding protocols, which offer great opportunities to combat powdery mildew fungus in future. From the grower's point of view, the most important thing to know is that host resistance might not be enough to control wheat powdery mildew disease; sound agricultural practices and judicious use of fungicides should also be considered.

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Antimicrobial Agents for Wheat Disease Management: Mode of Action and Its Application

6

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6.1 Introduction

Wheat is the largest cultivated crop in the world, occupying with an estimated production of over 766.5 million tonnes in 2019–2020 (http://www.fao.org/worldfoodsituation/csdb/en/), being a staple food in more than 40 countries and finds a significant share (35%) in the consumption basket of millions across the world. It is estimated that 85% and 82% of the global population depend on wheat for calories and protein, respectively (Chaves et al. 2013). Wheat meets 21% of the world's food demand and is grown on 200 M ha (494 million acres) of farmland globally (Tsvetanov et al. 2016). By 2050, world will face the challenge to meet the food demand of an estimated population of 9.6 billion. Feeding for growing population at the era of climate change requires optimizing the reliability, use of existing resources and environmental impacts of food production (Busby et al. 2017). Besides these challenges, wheat cropping system is facing numerous, unprecedented and constant threats owing to phytopathogens. In order to combat the serious losses caused by phytopathogens, different approaches of antimicrobial management methods should be taken up to minimize the relevant losses.

Wheat encounters the range of fungal diseases, namely leaf rust (*Puccinia recondita*); stem rust (*P. graminis* f. sp. *tritici*); stripe rust (*P. striiformis* f. sp. *tritici*); bunt (*Tilletia* sp.); smuts (*Ustilago* sp.) and others, which cause significant annual losses on a global scale. Fungicides are the important and feasible tool for managing pathogenic fungi. A diverse array of chemicals is available to manage fungal pathogens. The term 'fungicides' refers to anything that kills fungi or inhibits

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the growth of fungi. Besides its broader application in plant disease management, understanding the effect of fungicides on the beneficial activities of soil and plant microbiomes, a proper regulation for the use of fungicidal substances and their non-target organisms must studied in detail before its use in agriculture. The negative impact of constant use of fungicide is very difficult to estimate. Here, the chapter explains the knowledge on fungicidal substances, their mode of action and also possible side effects on non-target microorganism.

In addition to the above-mentioned fungal pathogens, there are many bacterial pathogens affecting wheat crop production, namely *Pseudomonas syringae* pv. *syringae* (bacterial leaf blight), *Clavibacter michiganensis* subsp. *tessellarius* (bacterial mosaic) and *Xanthomonas translucens* pv. *undulosa* (bacterial streak and black chaff). A comprehensive understanding of bacterial pathosystems is essential in order to reduce the losses caused by them by identifying their targets which helps in the optimum seasonal timings for deployment. The selection of chemical management of individual bacterial diseases depends upon the proper understanding of its modes of action, accessibility to pathogen on plant surfaces and susceptibility of the pathogen (Sundin et al. 2016).

From the past few decades, research has been focused on biological control of plant diseases keeping the negative impact of synthetic pesticides low on environment and biodiversity (Gholami et al. 2019). Microbial biological agents that are applied to crops for plant disease management have a wide range of modes of actions. They interact with plants by triggering resistance without direct interaction with the targeted pathogen or other mechanisms like modulating the growth conditions of pathogen (Kohl et al. 2019). Therefore, there is a possible need to understand the mode of action of microbial biological control agents to achieve optimum disease control.

The use of synthetic chemicals for the management of plant diseases has increased the production and productivity of wheat, which led to the success of green revolution. Yet, the indiscriminate use of inorganic chemicals and its residual effect on agricultural foods and commodities concerned the researchers to find alternative strategies that should be biodegradable as well as minimizing the cost of production for the sake of farmers. Botanical pesticides are good substitute to chemical pesticides which are eco-friendly and target specific. Botanical pesticides are derived from plants that can adversely affect the pathogens growth and are safe to the environment and human beings as well.

Furthermore, in the past decades, many advances in the use of technology such as nanotechnology has provided new avenues especially in the sustainable plant disease management. It is important to mention here that the nanotechnology has found promising potential in enhancing crop production and sustainability by improving shelf life, reducing toxicity and increasing the solubility of poorly water-soluble pesticides (Worrall et al. 2018; Kashyap et al. 2020). Use of RNAi technology as a method for disease suppression is a newly advancing avenue (Werner et al. 2020; Mann et al. 2008). This chapter, thus, aims to discuss the different antimicrobial compounds and their advances so far in managing the major diseases of wheat. It also focuses on newly emerging technologies and their success in efficient management of the pathogens.

6.2 Antimicrobial Compounds and Their Diversity

6.2.1 Agrochemicals

6.2.1.1 Fungicides

There are several ways to classify fungicides (Hermann and Stenzel 2019). Fungicide Resistance Action Committee (FRAC) has published a list of 43 groups of fungicides based on their mode of action and also many other criteria of classification based on their chemical composition and site of action, which are described in the following part of the chapter. There are few novel fungicides reported, whose mode of action is broad spectrum and also effective against powdery mildews and oomycetes fungi, namely proquinazid, fluopicolide, metrafenone, boscalid, fluopyram and carboxylic acid amide group of fungicides.

Rusts of wheat cause serious economic losses, and to manage the rusts, an antifungal protein from *Penicillium chrysogenum* (PAF) showed adverse effect on the germination of uredospores of *Puccinia recondita* f. sp. *tritici* by degenerative branching of germ tubes (Barna et al. 2008). The antifungal activities of N-arylbenzene sulfonamides have shown the control efficacy on wheat leaf rust (Kang et al. 2002). Kumar et al. (2017) reported that difenoconazole acts as a successful inhibitor of flag smut of wheat when applied as seed dressing. *Alternaria alternata*, which causes black point of wheat, was effectively inhibited by propiconazole at an EC50 of 3.38 mg/kg, as well as by Difenoconazole at an EC50 of 6.61 mg/kg (Honglian et al. 2005). The most commonly used fungicides for controlling stripe rust include demethylation inhibitors (DMIs) such as cyproconazole, epoxiconazole, fluquinconazole and picoxystrobin; succinate dehydrogenase inhibitors (SDHIs) such as fluxapyroxad, bixafen and benzovindiflupyr and quinone outside inhibitors (QoIs) such as kresoxim methyl, azoxystrobin, picoxystrobin and trifloxystrobin (Carmona et al. 2020). Some fungicide combinations such as azoxystrobin 20% + difenoconazole 12.5% SC, tebuconazole 50% + trifloxystrobin 25% w/w 75WG have been reported to increase yield of wheat genotypes as well as manage yellow rust of wheat, making it a potent short-term alternative for resistant varieties (Basandrai et al. 2020). Recent studies on fungicides for managing different diseases of wheat are enlisted in Table 6.1.

6.2.1.2 Bacteriocides

Antibiotics in wheat bacterial disease management have different mode of action that interferes with protein synthesis (erythromycin, chloramphenicol, clindamycin and lincomycin), cell wall components (cycloserine, vancomycin, bacitracin, penicillins, cephalosporins, etc.), cytoplasmic membranes (polymyxins, daptomycin, aureofungin and nystatin), binding of aminoacyl tRNA to ribosome (tetracycline) and others.

Bacteriocins are ribosomally synthesized antimicrobial peptides produced by microorganisms that form pores in the target cells, disrupting membrane potential and causing cell death as they produce small cationic peptides with antibacterial activity that serves as a defence strategy found in bacteria (Oscariz et al. 2000). The

Table 6.1 Diseases of wheat and the fungicides successfully evaluated against them

Disease	Pathogen	Fungicides	Reference
Rust	*Puccinia graminis* f. sp. *tritici*	Quinone outside inhibitors (QoIs), demethylation inhibitors (DMIs) and succinate dehydrogenase inhibitors (SDHI)	Oliver (2014)
Loose smut	*Ustilago tritici*	Systemic fungicides (like carboxin and difenoconazole)	Davis and Jackson (2017)
Spot blotch	*Helminthosporium sativum*	Carbendazim 0.1% at tillering and boot leaf stage	Yadav et al. (2015)
Head blight	*Fusarium graminearum*	Benzimidazole fungicides and prothioconazole	Machado et al. (2017), Marques et al. (2017a, 2017b)
Crown root	*Fusarium pseudograminearum*	Difenconazole-mefenoxam	Moya-Elizondo and Jacobson (2016)
Karnal bunt	*Neovossia indica*	Propiconazole 25EC (0.1%), Carbendazim 50 WP	Kumar and Singh et al. (2014)
Wheat blast	*Magnaporthe oryzae*	Tebuconazole 50% + trifloxystrobin 25%, azoxystrobin 20% + difenoconazole 12.5%	Roy et al. (2021)
Flag smut	*Urocystis agropyri*	Difenoconazole	Kumar et al. (2017)

bacteriocins utilize multiple regulatory components for the production of antimetabolites, which lyses the cells of the pathogens (Tariq et al. 2020). The range of naturally occurring bacteriocins is approx. 0.25–5 days and is largely dependent on the biocontrol strain, experimental conditions and the antibiotic under study (Arseneault and Filion 2017). Endophytic *Bacillus subtilis* isolated from wheat roots inhibits urediniospore germination of *Puccinia striiformis* f. sp. *tritici,* which causes wheat stripe rust (Li et al. 2013). The rhizospheric bacteria were also reported to significantly improve the crop yield as reported by Shivlata and Satyanarayana (2017) and by Lamont et al. (2017), while studying *Actinobacteria* and *Lactobacillus*, respectively.

6.2.2 Botanicals/Plant Extracts

The methanolic extract of *Corydalis ternate* suppressed the development of *Puccinia triticina* due to the presence of three isoquinoline alkaloids, namely dehydrocorydaline, stylopine and corydaline (Han et al. 2018). The plant extracts of garlic, clove, garden quinine, Brazilian pepper, Bit anthi mandarin, black cumin, white cedar and neem are found effective in controlling leaf rust caused by *P. triticina* by inhibiting the spore germination, thus, reducing the number of pustules on the leaf surface (Shabana et al. 2017). In addition to the outlined plant extracts, the plant extracts of henna, *Lawsonia inermis, Acalypha wilkesiana,*

Table 6.2 Essential oils or botanicals reported for the control of wheat diseases

Plant	Plant part used	Disease	Reference(s)
Melia indica	Leaf	Pre-emergence seed rot of wheat	Enikuomehin et al. (1998)
Azadirachta indica	Leaf	Rot of wheat	
Allium cepa	Clove	Rust of wheat	Sahayaraj et al. (2006)
Eucalyptus globus	Leaf	Leaf blight of wheat	Patil and Kulkarnia (2002)
Inula viscose (sticky fleabane)	Leaf	Powdery mildew of wheat	Wang et al. (2004)
Prosopis juliflora and *Oxalis corniculata*	Leaf	Leaf spot and leaf blight caused by *Xanthomonas sps*	Satish et al. (1999)
Aloe barbadensis ill.	Leaf	Head blight	Varma and Saran (2019)
Datura stamonium	Stem, leaf, root and flowers	Leaf spot caused by Curvularia lunata	
Piper nigrum Linn.	Leaf	Bacterial leaf streak	
Origanum hercleoticum	Leaf	Head blight	Devi et al. (2019a, 2019b)
Jacaranda mimosifolia	Leaf	Spot blotch	Naz et al. (2018)
White mustard	Seeds	Head blight	Drakopoulos (2020)

chinaberry, Melia azedarach, Punica granatum and Lantana camara have challenged leaf rust of wheat (Draz et al. 2019).

Essential oils (Eos) have been reported to be highly effective against plant pathogens in vegetables as well as cereals (Table 6.2). Choi et al. (2004) reported the reduction in powdery mildew of wheat and barley with the extracts of *Rumex acetosella* roots. The effectiveness of dill seed oil was evaluated by Monika (2016) in wheat. She observed that the seed extract and its fractions were able to successfully inhibit the growth of *Bipolaris sorokiniana*, *Alternaria triticina* and *Ustilago segetum* var. *tritici* to a considerable extent. The essential oils obtained from plants such as neem, aloe vera and cumin have been reported to be highly effective against soil pathogens such as *Rhizoctonia solani* and *Fusarium oxysporum*.

The use of botanicals has also accelerated with the increasing stress on eco-friendly management practices. A commercially exploited plant product, Milsana®, obtained from the *Reynoutria sacchalinensis* is reputed to be one of the best natural fungicides, as it is able to successfully control the growth of powdery mildew pathogen in a number of vegetable crops as well as ornamentals such as tomato, cucumber and begonia, and it has also been successful against downy mildews and rusts of fruits and vegetables (Daayf et al. 1995). A plant extract of *Melaleuca alternifolia* has shown good inhibitory action against powdery mildews, rust, downy mildews, blights diseases in vegetables, fruits and orchards, while being harmless to pollinators and other beneficial insects. Certain plant extracts have also been observed to be highly stable to heat treatment and exhibited high affectivity against a broad spectrum of microorganisms (Hsieh et al. 2001). The use of botanicals and EOs is highly effective as they contain a large number of bioactive compounds in various concentrations. The concentration of active compound varies with the plant part: *Salvia officinalis* contains α-thujanone at 55%, 30% and 18% in stems, leaves and flowers, respectively (Raveau et al. 2020). Extracts of *Macleaya cordata* have reportedly exhibited antifungal activity against *Blumeria graminis* and *Erysiphe graminis* due to the presence of benzophenanthridine alkaloids (Singh et al. 2020).

6.2.3 Microbial Formulations

Chen et al. (2018) have revealed that a compound secreted by *Pseudomonas piscium* (phenazine-1-carboxamide) directly affects the activity of *Fusarium graminearum* protein FgGcn5, which is a histone acetyltransferase of the Spt-Ada-Gcn5 acetyltransferase (SAGA) complex. The compound secreted by bacteria has led to deregulation of histone acetylation in *F. graminearum*; subsequently, suppression of fungal growth, virulence and biosynthesis of mycotoxin. *Bacillus* lipopeptides (surfactins, iturins and fengycins) were studied for their antagonistic activity for a wide range of phytopathogens and further in-depth studies have shed light on the fact that these lipopeptides can also influence ecological fitness of the producing strain colonization by stimulating host defence mechanisms (Bais et al. 2004). When *B. subtilis* strain 6051, a wild type treated to *Arabidopsis* root surfaces against *P. syringae* and visualized under confocal scanning laser microscopy, it revealed that the biofilm formation process includes the surfactin, a lipopeptide antimicrobial agent secretion. The mutant strain, M1 (deletion of surfactin synthase gene) of *B. subtilis,* was found ineffective as a biocontrol agent against *P. syringae* in both infectivity and in biofilm formation on either roots or on inert surfaces (Bais et al. 2004; Mahapatra et al. 2020). When wheat cultivars were inoculated with bacterial endophytes, they aided in phosphate solubilization, IAA production and siderophore production that worked synergistically to increase the overall growth and yield of the crop (Emami et al. 2019). The biocontrol by microbial formulations includes antibiosis, rhizospheric competition and plant growth promotion (Tariq et al. 2020). The addition of bioformulations was also reported to increase overall tissue health and physiology in many crops (Kumar et al. 2016). Wheat microbes involved in plant regulations and their habitat have been presented in Table 6.3.

6.2.4 Nanoformulations/Nanoparticles (NPs)

The study of the properties of structures that are smaller than 100 nm is called nanoscience. During the past decade, nanotechnology has gained prominence due to its wide spectrum application in agriculture and allied sectors with a potential of enhancing the sustainability of crop production in the era of climate change and is

Table 6.3 Wheat microbes involved in plant regulations and their habitat

Microbes	Habitat and function	Reference
Bacillus, Azospirillum and *Azotobacter*	Rhizosphere Nutrient and water uptake from soil	Verma and Suman (2018)
Azospirillum brasilense	Nitrogen fixing microbe Gibberlin and IAA production	El-Razek and El-Sheshtawy (2013)
Pseudomonas, Azospirillum and *Bacillus.*	PGPB Cytokinin production	Verma and Suman (2018)
Paenibacillus, Polymyxa and *Acetobacter*	Diazotrophs IAA and related compounds	Timmusk et al. (2014), Aarab et al. (2015)
Pseudomonas sps	Rhizosphere Phosphorous solubilization, siderophore, IAA and DAPG	Roesti et al. (2006)
Providencia sp. PW5	Rhizosphere HCN, IAA, P solubilization and Zn solubilization	Rana et al. (2012)
Acinetobacter calcoaceticus	Rhizospheric P solubilization, siderophore and IAA	Prashant et al. (2009)
Bacillus subtilis	Diffusible fungitoxic compounds	Villa-Rodriguez et al. (2019)
Arthrobacter, hizobium and *Bacillus*	IAA and P solubilization	Patel and Archana (2017)
Azospirillum sp.	Nitrogenase production	Singh et al. (2017)

being utilized in various precise forms as nanopesticide to enhance the efficacy through controlled release (Jasrotia et al. 2018; Kashyap et al. 2013). Using nanoparticles in plant disease management with agrochemicals enhances shelf life, site-specific uptake, increased solubility and minimizing toxicity and soil leaching (Kashyap et al. 2020).

The different kind of nanomaterial used in plant disease management is nanoemulsions, nanocapsules and metal NPs in polymers (Jasrotia et al. 2018; Kashyap et al. 2015). To meet the existing challenges in wheat production and productivity, advancement in nanotechnology is a ray of hope in deciphering the hurdles, though the application is in *nascent* stage. To study the antifungal and oxidative activity of chitosan nanoparticles to inhibit the effect of *Fusarium graminearum*, different concentrations of chitosan and their NPs were tested. The research findings indicated that the low molecular weight of chitosan and their NPs have strong antifungal activity. Further, it was also noticed that the molecular weight of NPs is one of the key determinants in deciding their antagonistic potential. High molecular weight NPs have abundant amino acids and, thus, due to their strong intra-molecular hydrogen bindings, fabricated cross-linked structures are formed, which are then no longer available to attach to *F. graminearum* cell surface (Kheiri et al. 2017a, b).

6.3 Mode of Action of Antimicrobial Agents

6.3.1 Agrochemicals

6.3.1.1 Fungicides

The fungicides used for the management of fungal diseases of wheat belong to a number of classes according to the FRAC classification. The benzimidazoles used for the management of higher fungi, such as *Fusarium graminearum,* inhibit the fungal growth by inhibiting the β-tubule assembly, leading to disruption of cell division in the fungus. The QoIs and SDHI, widely used for managing rusts of wheat, inhibit the ubiquinol oxidase and succinate dehydrogenase, respectively, thereby inhibiting the respiration. The DMIs, such as prothioconazole and difenoconazole, help in restricting the fungal growth by acting as a sterol biosynthesis inhibitor (FRAC code list 2018).

6.3.1.2 Bactericides

The bactericides used for management of bacterial diseases of wheat mainly effect the bacterial growth and development by inhibiting the amino acid and protein synthesis as seen in case of streptomycin and oxytetracycline. Others such as erythromycin inhibits the translation process in bacteria by binding to 50S ribosome (FRAC code list 2018).

6.3.2 Biocontrol Agents

Generally, the microbial antagonists employ a wide array of mechanisms in order to restrict the pathogen growth, which in turn affects the soil properties as well. It has been observed that *Pseudomonas* produces 2, 4-diacetylphloroglucinol (DAPG), an antibiotic which induces the host defences, thus protecting the plant indirectly against the pathogen attack (Iavicoli et al. 2003). Further, DAPG producers have been reported to be highly potent in root colonization, which further helps in suppressing the growth of harmful microbes in the wheat rhizosphere, by competing for available nutrients (Raaijmakers and Weller 2002). Some bioformulations such as *Bacillus mycoides* strain have been observed to produce antimicrobial enzymes including peroxidase and β-1, 3-glucanase in vegetable crops (Bargabus et al. 2003). Species of Bacillus and Pseudomonas trigger profuse root growth in the treated plants, which leads to an increased nutrient absorption by the plant roots. Recently, Araujo et al. (2020) reported that *Paenibacillus peoriae* SP9 and *Streptomyces fulvissimus* FU14 successfully inhibited the growth of *Pythium sp*. in wheat rhizosphere under both greenhouse and field conditions. Rojas et al. (2020) isolated a number of endophytes from wheat spikes grown under fields heavily infected with *Fusarium graminearum.* They observed that four isolates *Sarocladium strictum* C113L, *Anthrococystis floculossa* F63P, *A. floculossa* P1P1 and *Penicillum olsonii* ML37 had high biocontrol ability against *Fusarium graminearum.* In a similar study, Gholami et al. (2019) reported that *Coprinopsis urticicola* successfully colonized the root and crown of wheat seedlings leading to an inhibition of take-all disease of wheat. Principle microbial antagonists reported as biocontrol agents against wheat diseases have been mentioned in Table 6.4.

6.3.3 Botanicals

Essential oils (EOs) have been reported to be highly effective as antifungal, antibacterial and antiviral agents (Table 6.5). Antimicrobial actions of essential oils have been attributed to the presence of volatile compounds such as thymol and linalyl acetate, which affect the lipid fractions of the plasma membrane of the bacterial cell that leads to increased cell permeability resulting in leakage of ions. This starts a cascade of cytotoxic activities in the bacterial cell, which finally leads to the death of the bacterial cell (Oussalah et al. 2006). The EOs have been reported to inhibit the toxin secretion in a number of bacteria, which is controlled by modifying the transmembrane transport of toxins across the bacterial membrane into the environment (de Souza et al. 2010). The EOs of cloves, lavender, geraniums, roses and rosemary have been observed to exhibit anti-quorum sensing activities, which controls virulence, sporulation, bioluminescence, mating and other vital activities in bacteria (Faleiro 2011). Basil, fennel, oregano, citrus, lemon grass, rosemary and thyme have been observed to possess significant antifungal activity against the wide range of fungal pathogens. Among the studies conducted so far, thyme and oregano essential oils have been assessed to be the most effective in inhibiting the fungal growth. This has been attributed to the presence of carvacrol and thymol as main constituents, which disrupts the fungal cell membrane. In fungal cells, EOs affect the depolarization of the cell membrane, change the ionic influx and reduce the pH of the cells. The mitochondrial permeability in the outer and inner membranes is affected upon treatment with the EOs, which results in necrosis and ultimately apoptosis (Yoon et al. 2000).

6.3.4 Nanoantimicrobials

Wheat seeds are treated with chitosan (CS) at concentration of 2–8 mg/mL that significantly improved seed germination to recommended seed certification standards (>85%) and vigour at concentrations >4 mg/mL, in two cultivars of spring wheat (Norseman and Max), by controlling seed-borne *Fusarium graminearum* infection (Bhaskara Reddy et al. 1999). The application of various concentrations of CS and chitosan nanoparticles (CS/NPs) showed significant inhibition of both radial mycelial growth and number of colonies formed against *F. graminearum*. The application of 1000 and 5000 ppm concentration of CS and CS/NPs produced maximum inhibition of radial mycelial growth in comparison to the control, respectively (Kheiri et al. 2016).

Table 6.4 Microbes as potential antagonists of wheat diseases

Disease	Antagonistic microbe	References
Rusts of wheat	*Bacillus* and *Enterobacter* sp.	Wang et al. (2012) and Li et al. (2013)
	Verticillium lecanii, Erwinia herbicola and *Pseudomonas aurantiaca*	Allen (1982), Srivastava et al. (1985) and Kempf and Wolf (1989)
	Verticillium lecanii + *Paecilomyces fumosoroseus* and *Beauveria bassiana*	Hall (1981)
	Pseudomonas putida	Flaishman et al. (1996)
	Trichoderma harzianum, Streptomyces viridosporus, Bacillus subtilis and *Saccharomyces cerevisiae*	Eldoksch et al. (2001), Kalappanavar et al. (2008) and El-Sharkawy et al. (2015)
	Pseudomonas sp. and Erwinia sp.	Huang and Pang (2017)
	Bacillus subtilis, Bacillus polymyxa and *B. megaterium*	Omara et al. (2020)
	Combined application of arbuscular mycorrhizal fungi and *Azospirillum amazonense*	Ghoneem et al. (2015)
Tan spot, spot blotch and *Helminthosporium* leaf blight, fusarium head blight of wheat and septoria blotch	*T. harzianum* isolate T2, T5 and T7	Monte (2001), Mahmoud (2016)
Sharp eye spot	*B. subtilis* NJ-18	Peng et al. (2014)
Powdery mildew of wheat	Combined application of yeasts like *Rhodosporidium kratochvilovae* strain UM350, *Cryptococcus laurentii* strain UM108 and *Aureobasidium pullulans* strain LS30; *Tilletiopsis pallescens* BC0441 and *T. pallescens* BC0850	De Curtis et al. (2012) and Köhl et al. (2019)
Fusarium head blight disease of wheat and powdery mildew of wheat	*Bacillus subtilis* strain E1R-j	Gao et al. (2015) and Mahmoud (2016)
Wheat blast and black point complex of wheat	*Bacillus subtilis* BTS 3, *B. amyloliquefaciens* BTS 4, *Staphylococcus saprophyticus* BTS 5 and *B. amyloliquefaciens* BTLK6A	Surovy et al. (2017) and El-Gremi et al. (2017)
Fusarium head blight of wheat; take-all disease of wheat	*B. subtilis* D1/2 (DAOM 231163) and *B. subtilis* RC 218, *Brevibacillus* sp. RC	Chan et al. (2003), Nasraoui et al. (2007) Crane et al. (2014), Palazzini et al. (2016) and Liu et al. (2009)

(continued)

Table 6.4 (continued)

Disease	Antagonistic microbe	References
	263 and *Bacillus amyloliquefaciens*	
Fusarium head blight of wheat	*Lysobacter enzymogenes* strain C3	Jochum et al. (2006)
	Cryptococcus and *Brevibacillus* sp. RC 263	Schisler et al. (2002, 2006, 2014)
	Clonostachys rosea strain ACM941 (CLO-1) FHB	
Karnal bunt of wheat	*Pseudomonas fluorescens* (strains MKB 158 and MKB 249) and *P. frederiksbergensis* (strain 202)	Khan and Doohan (2009) and Vajpayee et al. (2015)
	Aureobasidium pullulans	Wachowska and Głowacka (2014)
	Trichoderma viride, *T. harzianum* and *Gliocladium deliquescens*	Sharma and Basandrai (2000)
	Trichoderma pseudokoningii, *T. lignorum*, *T. koningii*, *G. deliquescens* and *G. virens*, *Azotobacter chroococcum*	Amer et al. (2000)
Loose smut of wheat and black point complex of wheat	*Trichoderma viride*, *Gliocladium deliquescence, T. harzianum*, *Pseudomonas fluorescence* and *Bacillus subtilis*	Agarwal and Nagarajan (1992), Singh and Maheshwari (2001), Monaco et al. (2004) and El-Meleigi et al. (2007)
Black point complex of wheat	*Bacillus megaterium* B5, *B. amyloliquefaciens* B28, *T. harzianum* T37 and *Epicoccum* sp. E52	El-Meleigi et al. (2007)
Common bunt disease of wheat	*Streptomyces*, *Bacillus*, *Pseudomonas fluorescens*, *P. putida*, *Pseudomonas chlororaphis* MA 342, *Gliocladium* and *Trichoderma harzian*	Borgen and Davanlou (2000), McManus et al. (1993) and Kollmorgen and Jones (1975)
Take-all disease of wheat	*Phialophora radicicola* var. *radicicola*	Wong and Southwell (1980), Wong et al. (1996) and Mathre et al. (1998)
	Trichoderma koningii, *T. harzianum* and *T. viride*	Simon and Sivasithamparam (1989) and Zafari et al. (2008)
Wheat blast, *Magnaporthe oryzae Triticum* (MoT) pathotype	*Bacillus subtilis* strain 109GGC020	Chakraborty et al. (2020)

Table 6.5 Bioformulations for the management of wheat diseases

Disease	Bioformulations	Reference(s)
Stripe rust	*Bacillus subtilis* strain E1R-j	Li et al. (2013)
Loose smut	*Gliocladium virens* or *Tricoderma harzianum* with Vitavax@ 0.125%	Singh and Maheshwari (2001)
Tan spot	*Bacillus spp.* and *Fusarium sp.*	Larran et al. (2016)
Blast	*Bacillus subtilis* strain 109GGC020	Chakraborty et al. (2020)
Head blight	*Trichoderma* spp., *Cladosporium cladosporioides* and *Sphaerodes mycoparasitica* SMCD 2220–01	Kim and Vujanovic (2017)
Crown rot	*Lysobacter antibioticus* HS124	Kim et al. (2019)
Karnal bunt	*Trichoderma harzianum* (0.95% incidence) @4 g/kg seed	Srivastava (2014)
Leaf blight	*Trichoderma harzianum* (85.5% inhibition)	Kakraliya et al. (2017)

6.3.5 Plant Defence Activators

Apart from using antimicrobials that directly influence the growth of the pathogen, the use of plant defence activators has also gained momentum in the recent decade (Kashyap et al. 2018). The plant defence activators are instrumental in triggering the systemic acquired resistance (SAR) in the plants which lead to effective control against pathogen attack (Savadi et al. 2018). In addition to acting as a plant defence activator, benzimidazole-incorporated compounds are also known to possess plant growth-regulating properties and as a abiotic stress mediator (Magnucka et al. 2007). They were reported to reduce germination time, improve germination percentage as well as germination rate in treated wheat seeds (Hameed et al. 2019). It has been observed that salicylic acid (SA) and its analogue benzothiodiazole (BTH) effectively trigger SAR by inducing pathogenesis-related (PR) genes and other SAR marker genes (Gozzo and Faoro 2013). It was observed by Kashyap et al. (2018) that application of BABA in 1 mM was highly effective in restricting the growth and development of *Tilletia indica* in wheat kernels. They reported that the application of BABA leads to accumulation of PR proteins, which in turn triggered the SA pathway. Thus, priming of seeds with BABA served as an important management strategy for kernel bunt in wheat. Saccharin, another plant resistance inducer, was examined against various diseases of wheat. It was observed that saccharin triggered the genes encoding PR proteins and lipoxygenase, which restricted the development of *Zymoseptoria tritici* in wheat (Mejri et al. 2020). Saccharin was also found to restrict the growth of *Blumeria garminis* f. sp. *tritici*, the causal organism of powdery mildew of wheat. Further analysis revealed that that saccharin induced the expression of 15 defence-related genes, namely PAL, LOX, AOS, etc. (Zhao et al. 2020).

6.3.6 dsRNA Spray Technology

The available management strategies are either environmentally hazardous or harmful to non-target organisms. Hence, efforts are being made to develop a better alternative as compared to the traditional methods, which has brought RNA interference (RNAi) technology to the forefront (Manske et al. 2017; Mann et al. 2008). RNAi technology has a quick knockdown effect on the target genes, and hence, has been used against a number of pests and pathogens. Generally, two methods of application, that is, host-induced gene silencing (HIGS) and spray-induced gene silencing (SIGS), are used (Koch et al. 2013; Wang and Jin 2017). In HIGS, the plants are engineered to express the desirable dsRNA for providing long-lasting protection against the pest or pathogen. It has been used extensively in a large number of crops such as wheat, barley, rice and maize against a number of fungal pathogens (Sang and Kim 2020). However, the development of transgenic plants and its marketing in the commercial market are cumbersome, which is why SIGS has gained prominence (Christiaens et al. 2018).

SIGS is the topical application of the required dsRNA, in the form of foliar spray on the plant surface (Cagliari et al. 2018). The RNA, thus, applied is highly effective against pathogens with wide host range, as well as can be applied against multiple pathogens (Mumbanza et al. 2013). It does not require prior approval of the genetic technologies developed (Taning et al. 2020), it is environmentally non-persistent (Zhang et al. 2020) and highly specific against the target pathogen. It was observed by Werner et al. (2020) that SIGS of AGO and DCL genes in *Fusarium graminearum* helped in improving the resistance of the host plant against fusarium infection. The method has also been applied against *Botrytis cinerea* (Wang et al. 2016) and *Sclerotinia sclerotiorum* (McLoughlin et al. 2018) by targeting Bc-DCL1 and SS1G_05899 gene, respectively.

Although this new technology is gaining prominence, little is known about the mechanism of uptake of RNA by the pathogens, which is crucial for large-scale field applications. Further, RNA is easily degraded under the influence of environmental factors such as sunlight and rain, which mandates the use of a stable carrier and effective formulation. Studies have been conducted to incorporate dsRNAs into nanosheets of layered double hydroxide clay (Bioclay), which increased its longevity up to 20 days (Mitter et al. 2017). Extensive research on the uptake of dsRNA by the pathogens as well as development of formulations, which increase longevity and discourage resistance build up, would help profoundly in developing SIGS into an effective tool for management of pathogens (Wytinck et al. 2020).

6.4 Non-Target Effects of Antimicrobial Compounds

6.4.1 Fungicides

The non-target impacts of fungicides have documented to be mostly negative. It interferes with the functioning of soil microbiota, innate enzymatic activities as well as the biochemical processes of the soil. Benzimidazole fungicides, such as carbendazim, have deleterious effect on soil microbiota, and have also been reported to reduce hyphal growth in arbuscular mycorrhizal fungi (AMF). The application of fungicides has shown to impact the growth of potent biocontrol agents such as *Trichoderma harzianum* and *Aspergillus* spp., which are recognized for managing many important soil-borne pathogens (Virág et al. 2007). Fungicides, such as tridemorph and benomyl, are known to hinder the enzymatic activities of soil, which the biochemical soil processes and leads to poor soil health (Shukla 2000). The nutrient cycling of nitrogen is also impacted as the fungicides interfere with the nitrification and denitrification process (Kinney et al. 2005).

However, some fungicides have also been reported to induce growth and development of many beneficial microorganisms, such as AMF. Monkiedje et al. (2002) observed that the application of Metalaxyl leads to an increase in the mycorrhizal interactions in cereals such as maize. In terms of plant physiology in general, and wheat physiology in particular, limited studies have been conducted on the impact of fungicides on the plant. Strobilurins, such as azoxystrobin, has been shown to cause retardation in protein and chlorophyll degradation in the treated plants, as compared to non-treated plants. This has further shown to delay senescence in wheat leaf at later growth stages.

The use of fungicides has been reported to enhance the photosynthesis of flag leaves in wheat plants, beyond the normal duration. The grain number per spike and the 1000 grain weight increased significantly upon application of fungicides such as tebuconazole and azoxystrobin (Cromey et al. 2004). This has led to an increase in overall yield from the treated wheat plants. Overall, fungicides are not only effective against plant pathogens but are also responsible for long-term improvement of the treated plants.

6.4.2 Microbial Formulations

Microbial inoculations with different bacterial and fungal biocontrol agents have been a major area of research in the endeavour for achieving sustainable agriculture. It has been in the forefront for enhancing plant growth as well as uplifting the soil health conditions (Timmusk et al. 2017). Broadly, two types of microbial formulations are available: one occupies the ecological niche of the targeted pathogens and manages the pathogen population through parasitism, competition, predation or production of toxic antimetabolites; while the other comprises of those microbial formulations, which induces a resistance response in the plant, equipping it with protection against future invasions of the pathogens.

In case of wheat, application with *Trichoderma harzianum* was observed to induce profuse root and shoot growth, along with an increase in yield, number of grains per spike and 1000 seed weight. Similar results were obtained when wheat was treated with a consortium of bioformulations of *Bacillus polymyxa, Azospirillum lipoferum* and *Bacillus megaterium* (El-Gizawy et al. 2009). The bioformulations have been reported to occupy the plant rhizosphere and induce defence responses in the plants (Sharma et al. 2012). The application of BCAs also leads to an increase in rootgirth which helped in increased nutrient absorption by the plants, even in limited irrigation facilities. Further, *Trichoderma harzianum* was observed to aid in phosphate solubilization, which increased its availability to the plants (Singh 2010).

6.4.3 Nanoformulations

The use of nanoparticles (NPs) has been found to be eco-friendly and a cheap alternative approach towards the management of plant diseases (Prasad and Swamy 2013). The zinc oxide (ZnO) and magnesium oxide (MgO) NPs have been reported to be highly effective bactericides as well as door controlling agents. They have found their use in post-harvest pathogen management as well as food industry (Shah and Towkeer 2010). NPs in properly capsulated forms aid in slow release of the active ingredient, which helps in better penetration through the cells of bacteria and fungi, leading to better results as compared to conventional agrochemicals.

Nanoformulations have been evaluated for their effects on plants as well as the soil microbiota. In certain cases, nanoformulations have been shown to exert toxicity upon the treated media (VandeVoort et al. 2012), as well as the plant physiology (Anjum et al. 2013). However, the beneficial effects of nanoparticles are more pronounced in various studies. It has been observed that the adequate dose of AgNPs has the ability to enhance the nitrogen cycle by increasing the nitrate reduction in *Azotobacter*, with a 2.1- to 3.3-fold upregulation in nitrifying genes, which indicated the high sensitivity of the process towards silver. A shift in the microbial community has also been observed upon application of different nanoparticles in the soil. The microbial population was observed to develop silver-tolerant denitrifying species, indicating resistance and recovery of microbial populations upon treatment with nanoparticles (Throbäck et al. 2007). The stimulating effect of nanoparticles was observed by Salama (2012) in case of AgNPs when the treatment was applied in maize and cowpea. The NPs reportedly stimulated the root growth and increased synthesis of carbohydrates and chlorophyll, with increased protein content.

6.5 Field Applications of Antimicrobial Compounds

6.5.1 Fungicides and Bactericides

There are a diverse range of mode of applications and doses for the use of fungicides and bactericides for the management of wheat diseases (Table 6.3). Foliar spray, seed treatment, soil applications, fruit protectants, dusting on the affected surfaces, etc. are some of the methods of applications. For the treatment of rusts, leaf spots and leaf blights, spraying with fungicides of the triazole group, such as hexaconazole, or dithiocarbamates (Mancozeb), or benzimidazoles such as carbendazim is used. In general, it has been observed that 14-α-demethylation inhibitors (DMIs), quinone outside inhibitors (QoIs) and succinate dehydrogenase inhibitors (SDHI) are highly effective against rusts of wheat (Oliver 2014). In case of tan spot, the QoIs (e.g. pyraclostrobin) has been found to be more effective as compared to DMIs (e.g. propiconazole) (Jørgensen and Olsen 2007).

In wheat, grain infecting diseases such as loose smut and Karnal bunt cause significant yield losses. For management of loose smut, seed treatment with tebuconazole, of the Triazole group, is recommended. The use of Benlate @ 0.2% or Vitavax @ 0.2% can also be done as seed treatment. For the management of Karnal bunt, the seed treatment with copper carbonate or Thiram @ 3 g/kg seed is recommended. Spray of Carbendazim @ 0.1% can also be applied for disease management (Singh 2018).

For management of fusarium head blight, fungicides are considered to be an effective management tool. However, the use of triazoles, DMIs or their combined application is only able to manage the disease up to 30%–60% (McMullen et al. 2012). Fan et al. (2013) attributed the intrinsic resistance of *Fusarium graminearum* to triazoles.

For the management of wheat blast, Rios et al. (2016) recommended integrating the genetic resistance with fungicide treatment for effective disease management. Maciel (2011) observed that foliar fungicides were effective in reducing the disease incidence up to 50%. Further, the efficiency reduces considerably with warm and humid weather conditions, that is, around 25 °C with a wetting period of at least 10 h (Cardoso et al. 2008). Researchers have observed that repeated and large-scale use of QoIs have resulted in the development of a fungicide-resistant allele in almost 90% of tested isolates in South America (Castroagudín et al. 2015). Some fungicidal studies conducted on different wheat diseases are illustrated in Table 6.1.

When applying fungicides and bacteriocides for pathogen management, the attributes of the pathogen (host range, monocyclic/polycyclic and inoculum pressure), the host (stage of crop, impact of agrochemical on yield and degree of susceptibility of the host to the pathogen) and the environment (rain, temperature, dew and relative humidity) need to be taken into consideration. It is recommended to use fungicides that have a combination of preventive and protective mode of action. For example, in case of leaf rust of wheat, a combination of DMI plus SDHI or QoI was found ideal for managing the disease (Carmona et al. 2020). The number of applications and dose need to be kept at optimum as overspraying might lead to resistance development against the agrochemicals. Regular scouting of the field needs to be done so as to observe any symptoms of re-infection, after the application of fungicides/bacteriocides.

6.5.2 Bioformulations

A number of methods of applications of bioformulations have been devised so far. The effective utilization of the agents requires an intensive knowledge of the microbes, the treated plants and the environment upon which the management strategy is to be applied. The application can be in the form of inundated release, where a large volume of biocontrol agent, such as *Trichoderma harzianum* and *Pseudomonas fluorescens* (Heydari et al. 2004), is applied on a particular site, as seed coating, on soil at the site of seed placement or on fruits prior to storage (Janisiewicz and Peterson 2004), and this leads to a reduction in the pathogen count in the proximity.

Another method of application is the inoculative release of BCAs in smaller quantities, which multiplies on site and leads to pathogen control. Here, the BCAs spread to the other plant parts, as seen in case of non-toxic strains of *Aspergillus flavus* on wheat seed, which spread to different parts of the plant as well as soil, and replace aflatoxin producing strains of Aspergillus (Islam et al. 2005). The biocontrol agents are widely available in different forms of solid or liquid formulations. Among granular bioformulations, the wheat-based bioformulations of rhizobacterium *Pseudomonas trivialis* X33d have been reported (Mejri et al. 2013).

Some growers also apply BCAs on an occasional basis, so as to keep the pathogen population below a threshold level. In such cases, hypovirulent strains of the pathogen are applied, which provide protection to the treated plants against the virulent strains (Milgroom and Cortesi 2004). For management of seed-borne pathogens, seed treatment with BCAs such as *Trichoderma viride* @ 4 g/kg or *Pseudomonas fluorescens* @ 10 g/kg of seed is generally followed. For soil application, the BCAs are mixed with FYM or organic manures prior to application, which helps in the proliferation and spread of the agents in the soil. Some successful applications of bioformulations are illustrated in Table 6.5.

6.5.3 Essential Oils and Plant Extracts

Many activities have been carried out to find the adequate quantity of essential oils required to successfully manage the plant pathogens. In greenhouse experiments, soils, containing virulent strains of *Ralstonia solanacearum,* were treated with 700 mg/L of soil with essential oils obtained from lemon grass, thymol and palmarosa oil by Reitz et al. (2008). It was observed that the pathogen population was negligible in treated soils. Tomato seedlings, when transplanted in the treated soils, resulted in 100% wilt free seedling growth, indicating the high efficacy of the treatments.

Table 6.6 List of diseases of wheat successfully managed by plant extracts

Disease	Plant extracts	References
Leaf rust	Neem extract, clove and garden quinine *Lantana camara, Lawsonia inermis* and *chinaberry extract*	Shabana et al. (2017) and Draz et al. (2019)
Fusarium head blight	Cinnamon, clove and *Ocimum tenuiflorum* P-coumaric acids and phenolic acid derivatives Tillecur Pure yellow mustard and pure oriental mustard extract	Kalagatur et al. (2015), Gauthier et al. (2016), Drakopoulos et al. (2019) and Drakopoulos (2020)
Wheat blast	Methanol extract from *Catalpa ovata*	Cho et al. (2006)
Karnal bunt	Clove oil and oregano oil *Lantana camara* extract	Karaca et al. (2017) and Kumar et al. (2017)
Alternaria leaf spot	Neem leaf extract @ 10%, Eucalyptus and lavender extracts	Kakraliya et al. (2017) and Zaker and Mosallanejad (2010)
Spot blotch	Buds, leaves and bark extracts of *Eucalyptus camaldulensis*, garlic cloves and ginger rhizome extract	Bahadar et al. (2016) and Prashanth et al. (2017)

In case of seed attacking pathogens, the use of essential oils as oil dilution dips has been found to be the most effective. The wheat seeds are dipped in EO dilutions for 1 h, and then transferred to blotting papers. A study conducted by Karaca et al. (2017) observed that doses of clove oil and oregano oil over 3% and 2%, respectively, completely inhibited the growth of bunt fungus on wheat seeds. Over 60% fungal inhibition was observed when treated with mint oil at 6% and 7%. However, intermediate doses resulted in the inhibition of seed germination as well.

The root exudates of wheat have been reported to inhibit the growth of a number of pathogens, such as *Gaeumannomyces graminis*. Mathiassen et al. (2004) observed the presence of DIMBOA in the exudates of wheat roots, which represses the growth of root-pathogenic fungi. Debsharma et al. (2021) tested the efficacy of five botanical oils against *Bipolaris sorokiniana* of wheat. They reported highest inhibition of fungal growth by clove oil followed by ginger oil at 55.27% and 51.45%, respectively. Neem oil reported least efficacy against the pathogen. Table 6.6 enlists various research efforts made for evaluation of plant extracts for the management of major diseases of wheat.

6.5.4 Nanoparticles

Even though fungicides are highly efficient is plant disease management, large-scale use leads to environmental pollution, causes loss in biodiversity and even contributes towards the emergence of new virulent pathogen species (Rai et al. 2015). The use of

Table 6.7 List of wheat diseases managed by nanoparticles

Nanoparticles	Diseases	References
TiO_2 NPs by plant extracts of *Trianthema portulacastrum*	Wheat rust	Irshad et al. (2020)
Chitosan (CS) and chitosan nanoparticles (CS/NPs), and copper nanogel (220 ± 10 nm)	Fusarium head blight	Kheiri et al. (2017a, 2017b) and Brunel et al. (2013)
Nanogold particle in surface plasmon resonance-based immunosensor	Karnal bunt	Singh et al. (2010)
Silver nanoparticles (20–30 nm)	Spot blotch	Jo et al. (2009)
Nanochitin whiskers	Crown rot	Liang et al. (2018)
Silicon nanoparticles	Powdery mildew	Mahmoodzadeh et al. (2013)
Copper nanoparticles from leaves of *Eucalyptus globules*	Loose smut	Swamy and Nargund (2017)
Silver and copper nanoparticles	Eyespot disease	Belava et al. (2017)

nanoparticles for plant disease management has gained popularity in the recent decades as it is non-invasive, easy to handle, site specific, highly effective and is capable of delivering antimicrobial agents without any collateral damage (Nikhil and Bharat 2004). NPs have been used in a number of formulations such as nanogels, nanoemulsions, nanospheres, nanocapsules and metallic nanoparticles. Nanomaterials possess a wide array of desirable traits, such as crystallinity, solubility, stability and biodegradability, which make them apt as carriers of bioformulations, fungicides and other antimicrobial compounds (Yan et al. 2005; Bouwmeester et al. 2009).

Among the nanoparticles, silver has been investigated the most for its antimicrobial properties (Russell and Hugo 1994). Silver, in its ionic and metallic forms, has been able to restrict the growth of *Bipolaris sorokiniana* infection in wheat. The growth inhibition was found to correlate positively with the concentration of NPs, and the inhibition was apparent within 1 h of the treatment in in vitro conditions. Jo et al. (2009) confirmed that silver, in its ionic form, was able to inhibit the growth of *B. sorokiniana* at a concentration as low as 2.2 ppm, within 1 h of application.

The study of nanoparticles and their impact has also been conducted on different wheat pathogens (Table 6.7). It was observed that the silicon nanoparticles (SNPs) obtained from *Pseudomonas putida* was found to be the most effective against powdery mildew of wheat at 150 ppm, as compared to other nanoparticles. Similar results were observed in SNPs obtained from *Trichoderma harzianum,* which caused a reduction of 82% in in vitro conditions. TiO_2 was observed to cause an increase in chlorophyll content in treated plants at a concentration of 1000 mg/l (Mahmoodzadeh et al. 2013). Carbon nanotubes (CNTs) were observed to cause root elongation at 75% wt CNTs in wheat by Miralles et al. (2012). Copper oxide nanoparticles caused an increase in root biomass, upon treatment @500 mg/kg, when studied by Dimkpa et al. (2012).

Liang et al. (2018) studied the antifungal activity of nanochitin whiskers, a rod-like cationic particle, against crown rot of wheat. They observed that the treatment was able to effectively inhibit the fungal growth as well as conidial formation in vitro at 30 and 300 ppm. The seedling studies revealed that seed treatment with a mixture of nanochitin whiskers and tebuconazole led to a disease inhibition of as high as 90.02% against *Fusarium graminearum* at 30 ppm of NCs.

Studies on the combined effect of nanoparticles and bioformulations have also gained interest in the recent years. Ibrahim et al. (2020) worked on the synthesis of silver nanoparticles, obtained from endophytic bacteria present in garlic, and studied it effectively against *Fusarium graminearum*, the head blight pathogen of wheat. They observed an inhibition of fungal mycelial growth as high as 80.56% in vitro at 20 μg/ml damages to the fungal cell wall, and other disruptive morphological changes were observed in the treated pathogen. Similar results were obtained by other researchers when working with AgNPs against *Trichosporon asahii, Botrytis cinerea* and *Alternaria alternata* (Xia et al. 2016).

6.6 Integrated Management of Diseases of Wheat Using Antimicrobials

A plethora of studies have been conducted to develop effective management strategies for mitigating the effects of different pathogens of wheat (Fig. 6.1). The ever evolving population of the pathogens makes it difficult to frame a definite management strategy for all the pathogens. However, with the advancement of biotechnological tools and a greater understanding in pathogen biology and epidemiology, utilizing proper management strategies as well as proper timing of the strategies have shown to successfully inhibit the pathogen growth. Some recent management strategies for the management of wheat diseases are enumerated in Table 6.8.

In case of rust, use of resistant varieties is the preferred choice; however, the emergence of new races of the pathogen has rendered the choice of resistant varieties ineffective. For the management of rust, quinone outside inhibitors (QoIs), 14-ademethylation inhibitors (DMIs) such as hexaconazole and the recent use of succinate dehydrogenase inhibitors (SDHI) are effective (Duplessis et al. 2012).

For Karnal bunt, it has been observed in various studies that seed treatment alone is not sufficient for management of the pathogen. A combination of seed treatment and foliar spray, using chemicals such as propiconazole, biocontrol agents and plant extracts such as that obtained from *Lantana camara,* has been observed to exhibit cent per cent disease inhibition (Kumar and Singh 2014).

Wheat blast has posed to be a major threat in Bangladesh in the recent years. However, the efficacy of a particular group of fungicide alone has been questionable. Seed treatment of wheat grains with fungicides has also been studied to inhibit the initial infection by the pathogen. Although the disease cannot be prevented entirely using seed treatments, it has proved to be an effective tool for management of seed-borne diseases (Bockus et al. 2015).

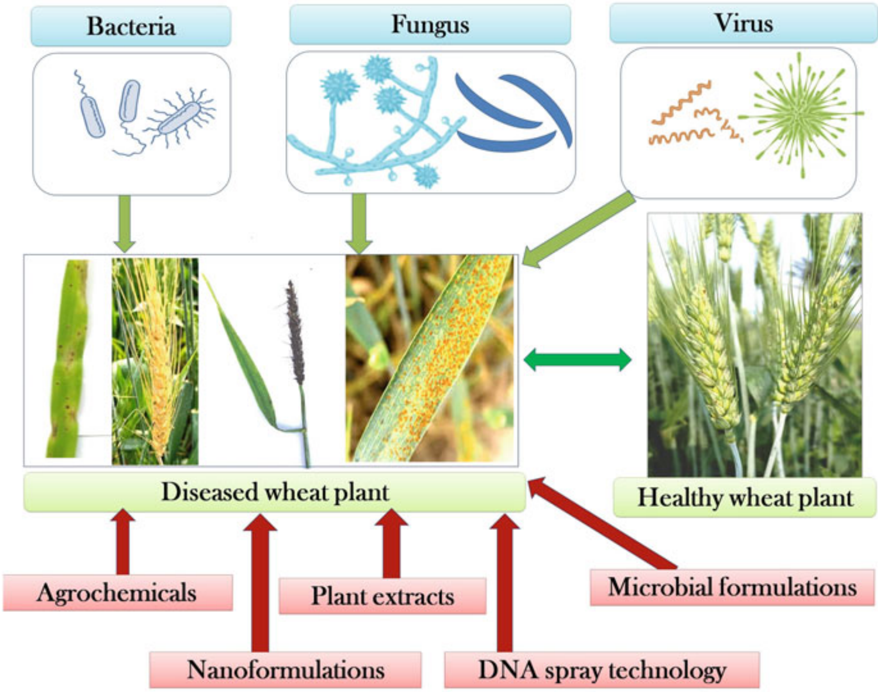

Fig. 6.1 Diagram presenting the used of different antimicrobial compound against wheat diseases

Plant diseases are highly complex in their interaction with the plants. Hence, a greater understanding and in-depth knowledge of their mechanisms of infection and interactions are required to keep the pathogen population under the stipulated threshold. New pathogens such as wheat blast are emerging and causing significant losses to the crop (Kumar et al. 2021). It is, thus, crucial to not utilize the management tools as individual approaches, but rather as a holistic measure to keep the pathogen population in check.

6.7 Research Gap and Future Outlook

Over the past few decades, a dire need for the development of the integrated use of different antimicrobial compounds has been felt by researchers all around the globe. Although the chapter has discussed the plethora of beneficial impacts that the antimicrobials have on the plant physiology as well as the soil ecosystem, there are many areas where further research needs to be conducted.

The ill effects of chemical antimicrobials have been documented in several researches (Abad et al. 2007). The use of fungicides and bacteriocides leads to environmental degradation and causes significant damage to the ecosystem. The injudicious use of most antimicrobial leads to environmental instability and

Table 6.8 Antimicrobials utilized for management of wheat diseases

Disease	Antimicrobial	Mode of application	References
Wheat rust	Triazoles such as triticonazole, flutriafol and carboxamide fluxapyroxad	Seed treatment	Wallwork and Garrard (2020)
	Mixture of quinone outside inhibitors (QoIs) and 14a-demethylation inhibitors (DMIs)	Foliar spray	Oliver (2014)
	Mentha pulegium EO	Foliar spray	Atlantica (2019)
	Neem extract, clove and garden quinine	Seed soaking and foliar spray	Shabana et al. (2017)
	TiO_2 NPs by plant extracts of *Trianthema portulacastrum*	In vitro assay	Irshad et al. (2020)
Spot blotch	Propiconazole + Trifloxystrobin; seed treatment with Carboxin 37.5% + Thiram 37.5% WS @ 2.5gm kg-1 seed with two sprays of Propiconazole 25% EC @ 0.1% at boot leaf stage and 20 days after first spray	Foliar spray, both seed treatment and spray	Kutcher et al. (2018), Singh et al. (2014) and Mahapatra and Das (2013)
	Buds, leaves and bark extracts of *Eucalyptus camaldulensis,*	Foliar spray	Bahadar et al. (2016)
	T. harzianum and *P. fluorescence* (1:1 ratio)	Seed soaking and foliar spray at seed, seedling, tillering and symptoms initiation stage	Yadav et al. (2015)
	Inducer chemicals salicyclic acid (10–4 M) and $CuSO_4$ (10–4 M and 10–5 M)	Seed treatment and foliar spray	Devi et al. (2019a, 2019b)
	AgNPs	Foliar spray	Mishra et al. (2014)
Fusarium head blight	Triazoles such as tebuconazole; benzimidazole fungicides, prothioconazole, tebuconazole + prothioconazole (TEBU +PROT; Prosaro); prochloraz	Foliar spray	Paul et al. (2008), Machado et al. (2017), Marques et al. (2017a, 2017b), D'Angelo et al. (2014) and Tini et al. (2020)
	Bacillus subtilis RC 218 and *Brevibacillus sp.* RC 263; *Aureobasidium proteae; Phoma*	Foliar spray	Palazzini et al. (2016), Comby et al. (2017), Schöneberg et al. (2015), Gong et al. (2015);

(continued)

Table 6.8 (continued)

Disease	Antimicrobial	Mode of application	References
	glomerata; Trichoderma spp.; *Shewanella algae* YM8; *Lactobacillus* species; Tetramycin; Sarocladium zeae Lysobacter enzymogenes		Baffoni et al. (2015), Shi et al. (2020), Kemp et al. (2020) and Zhao et al. (2019)
	Cinnamon, clove and *Ocimum tenuiflorum*	In vitro study	Velluti et al. (2004) and Kalagatur et al. (2015)
	Biofumigation with Indian mustard, clover, white mustard	Field trials	Drakopoulos (2020)
	ZnO NPs, chitosan (CS) and chitosan nanoparticles (CS/NPs)	Foliar spray	Savi et al. (2015) and Kheiri et al. (2017a, 2017b)
Karnal bunt	Propiconazole 25% EC	Seed treatment and foliar spray	Kumar and Singh et al. (2014)
	Trichoderma viride	Seed treatment and foliar spray	Sharma and Basandrai (2000)
	Propiconazole 25% EC (ST) + one spray *T. viride* + one spray *Lantana camara*	Seed treatment and foliar spray	Kumar and Singh et al. (2014)
Blast	Mancozeb plus Tricyclazole, tebuconazole; epiconazole + Pyraclostrobin	Foliar spray	Kohli et al. (2011), Rios et al. (2016)
	Potassium phosphate	Foliar spray	Cruz et al. (2011)
	Chaetomium globosum strain F0142	In vitro assay	Park et al. (2005)
	Methanol extract from *Catalpa ovata*	In vitro assay	Cho et al. (2006)

development of resistant virulent pathogens over time. Thus, the optimum doses of these compounds need to be assessed and utilized. There is a need to develop more stable, biodegradable products that have lower toxicity to the non-target organisms.

In terms of bioformulations, greater understanding of the ecology of the agents needs to be developed so as to tap the maximum potential of the biocontrol agents. It is the utmost need to develop bioformulations that have diverse mechanisms against the pathogens. Efficient application methods need to be formulated in order to increase the efficacy. In the recent years, studies have been conducted on the incorporation of bioformulations into nanoparticles, and it has shown highly promising results. However, more work needs to be done to generate novel biocontrol strains which can inhibit the rapidly evolving pathogen population with greater ease. Introducing new strains and mechanisms of fungal/bacterial plant pathogens are very diverse and their pathogenicity is different on host plants, it is, therefore, very important to look for new and novel biocontrol microorganisms with different mechanisms.

As discussed in the chapter, essential oils and botanicals can also serve as important tools in the management of the plant diseases. However, research needs to be conducted to identify more sources of antimicrobial extracts. Inherent sources of plant extracts, such as host plant volatiles, need to be identified as done by Schalchli et al. (2012) in wheat against *Gaeumannomyces graminis var. tritici*. Advanced breeding techniques need to be utilized to generate plants with higher quantities of antimicrobial compounds.

It has been observed that NPs develop a highly reactive interface with their surrounding environment, owing to their high surface-to-volume ratio (Orts-Gil et al. 2011; Kashyap et al. 2013). Further, many popularly used metallic NPs are reported to trigger stress responses in plants, which lead to ROS accumulation and disrupt the physiological and biochemical processes such as photosynthesis (Bujak et al. 2011; Keller et al. 2013). Thus, there is a pressing need for creating standardized criteria for synthesis and application of NPs on a large scale, with a view of least damage to the ecosystem. The characteristics of NPs need to be studied in greater detail to account for the occasional toxicity and damage to the environment.

6.8 Conclusion

The mandate for plant disease management is to keep the pathogen under a threshold level, while maintaining the ecological stability, plant health and ensuring the food security at the same time. Wheat is one of the most popular staples worldwide, but its availability is threatened by the presence of ever-evolving pathogen populations. Over the years, many antimicrobial compounds have been developed and discovered in order to manage the emerging and existing pathogens. The available technologies, when juxtaposed with biotechnology, have shown great promise in the field of agriculture. The integrated use of antimicrobial has extended the capability of the individual compounds to a much elevated level. However, the management of pathogens is a dynamic process that requires constant evolution of the available antimicrobial weapons as well. The available tools at our disposition need to be studied and developed further to generate environmentally viable, economically feasible and socially acceptable antimicrobial compounds, which can manage the plethora of pathogens with greater efficiency and ease.

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Integrated Management of Barley Diseases: Current Status and Future Research Priorities

7

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7.1 Introduction

Barley (*Hordeum vulgare*) is a primitive sacred cereal grain, which contributes nearly 12% of the global coarse cereal production. Globally, it occupied fourth rank among cereals. It is an important cereal grain crop in India, which has been cultivating since ancient time. Barley is frequently being described as the most cosmopolitan of the crops. It is considered a crop of marginal farmers due to its low input requirement and better adaptability to drought, salinity, alkalinity and marginal lands (Verma et al. 2012a, b). It is an important winter cereal crop in India. Rajasthan, Uttar Pradesh, Haryana, Punjab, Madhya Pradesh, Uttarakhand and Himachal Pradesh are major barley growing districts of India. Rajasthan occupies the highest area and production of barley followed by Uttar Pradesh and Haryana. The agro-climatic situations of Rajasthan are quite suitable for barley cultivation. During the last decade, demand of malt barley in domestic market for industrial utilization has increased. The water availability may crucial and a limiting factor for growing crops needs more irrigation and area under barley cultivation is expected to increase in Rajasthan due to climate change.

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7.2 Barley Uses

Barley grain is used as feed for animals, malt for industrial uses and human food. Its straw is used as animal fodder, bedding and cover material for hut roofs. Barley being a fast-growing crop with high biomass in early stages has been recognized as potential dual-purpose crop for both grain and green fodder. In India, about 70% of the total barley production is being utilized as animal feed. The second largest use of barley is malting purpose. Barley is most preferred for good quality malting because husk protects the coleoptiles during germination process which provides aid in filtration and relatively higher starch hydrolysing activity in barley as compare to other cereal grains. Malt is mostly utilized in brewing, energy drinks, flavouring agent in a variety of foods and for medicinal syrups (Sarkar 2012; Verma et al. 2012a, b). The utilization of barley in malting and brewing industries has increased many folds in recent years due to heavy consumption of beer and other malt-based products in many countries including India. The industrial requirement of barley is about 3.5–4.0 lac metric tonnes and it is growing annually at a rate of 10%. About 20–30% of the total barley production is utilized for malt preparation. Many malt companies used contract farming for production of the two-row barley in the states of Rajasthan, Punjab, Haryana, Utter Pradesh and Uttarakhand (Kumar et al. 2014). The barley products like sattu, dalia and chapatti are still a stable food for every traditional families of Rajasthan. The use of husk-less barley, mainly confined to tribal areas of hills, is now becoming popular all over the country as food purpose barley. The lifestyles diseases like hypertension, depression, obesity, heart problems, type II diabetes, decline in immune system, etc. appear to increase in frequency all over the world including India. Nowadays, barley is being recognized as such cereal grains having potential health benefits (high antioxidant and beta glucan content). The beta glucan in barley, which is a major component of soluble fibre, has been reported to bring down blood cholesterol levels besides providing other health benefits (Brennan and Cleary 2005; Pins and Kaur 2005). The whole grain barley contains phytochemicals including phenolic acids, flavonoids, lignans, tocols, phytosterols and folate which exhibit strong antioxidant, antiproliferative and cholesterol lowering abilities (Idehen et al. 2017). Barley-based multigrain flour, bread, cookies etc. are being consumed very commonly (Patel et al. 2008; Verma et al. 2012a, b). Barley has always been considered as a sacred cereal in Indian culture and is used in several religious ceremonies. Latest findings on its health benefits have confirmed its importance given by the ancient people. Regular consumption of barley products coupled with “Yoga” can help to boost immune system to fight against infectious diseases and maintain good health under the present stressful life style.

7.3 Crop Scenario

Globally, barley is grown in about 51.15 million hectares area with a production of 158.98 million tonnes (FAOSTAT 2020). In India, barley is cultivated on about 0.62 million hectare area with production of 1.59 million tonnes and productivity of 25.7 q/ha (Table 7.1; ICAR-IIWBR 2020). Area, production and yield of Indian barley during last decade have been shown in Fig. 7.1. Rajasthan is the largest state that occupied the highest area, 46.0% (0.288 million ha), and >52% share in production (0.83 million tonnes) of barley followed by Uttar Pradesh, Madhya Pradesh and Maharashtra (Table 7.2; Fig. 7.2; ICAR-IIWBR 2020).

Table 7.1 Recent trends in the area and production of barley in India

Year	Area (000 ha)	Production (000 tons)	Productivity (q/ha)
2010–2011	699.0	1564.0	22.4
2011–2012	643.4	1618.0	25.1
2012–2013	695.0	1743.2	25.1
2013–2014	674.0	1830.0	27.1
2014–2015	707.0	1613.0	22.8
2015–2016	589.0	1438.0	24.4
2016–2017	656.3	1747.5	26.6
2017–2018	661.7	1772.9	26.8
2018–2019	575.6	1633.0	28.4
2019–2020	618.4	1590.0	25.7

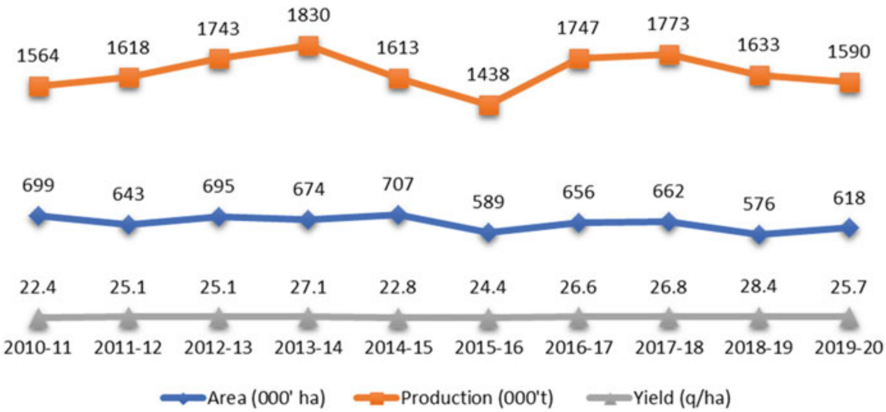

Fig. 7.1 Area, production and yield of Indian barley during the last decade

Table 7.2 Trends in area, production and productivity of barley in Rajasthan

Year	Area (Lac ha)	Production (Lac tonnes)	Productivity (q/ha)
2010–2011	3.28	8.58	26.2
2011–2012	2.78	7.89	28.4
2012–2013	3.07	8.53	27.7
2013–2014	3.09	9.42	30.4
2014–2015	3.41	8.41	24.7
2015–2016	2.56	7.66	29.9
2016–2017	27.59	8.41	30.5
2017–2018	2.74	8.76	32.0
2018–2019	2.56	7.55	29.5
2019–2020	3.71	10.82	29.1

Source: www.agriculture.rajasthan.gov.in.

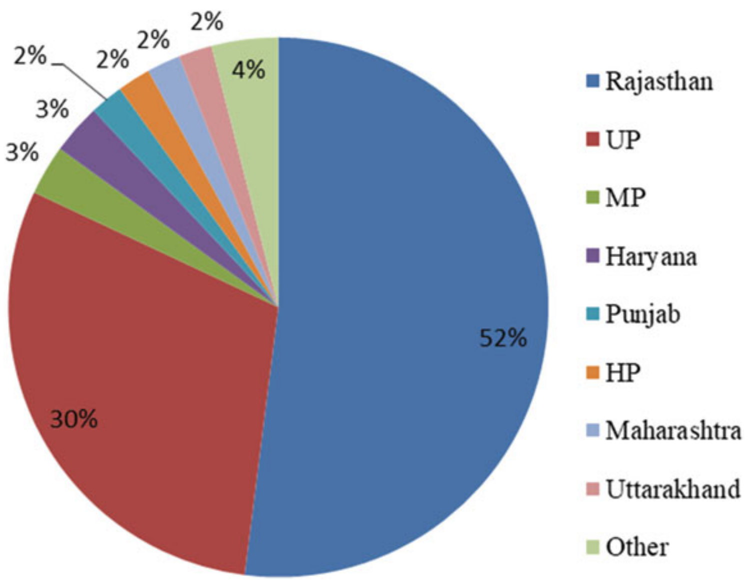

Fig. 7.2 Production share of major barley growing states of India

7.4 Important Barley Diseases in India

Like the other cereals, barley also encounters different plant pathogens (Table 7.3) and succumbs to various diseases which result in significant yield reduction and poor grain quality (Kashyap et al. 2021). Further, introduction of high-yielding barley varieties requiring higher fertility and moisture conditions resulted in more attack by few pathogens. Mathre (1997) mentioned 80 different infectious diseases in his "Compendium of Barley Diseases." However, stripe rust or yellow rust (*Puccinia*

Table 7.3 List of barley diseases and their causal organism

Fungal diseases	Causal organism
Anthracnose	*Colletotrichum cereale*
Cephalosporium stripe	*Hymenula cerealis* *Cephalosporium gramineum*
Common root rot, crown rot and seedling blight	*Cochliobolus sativus* *Bipolaris sorokiniana* *Fusarium culmorum* *Fusarium graminearum* *Gibberella zeae* [teleomorph]
Downy mildew	*Sclerophthora rayssiae*
Dwarf bunt	*Tilletia controversa*
Ergot	*Claviceps purpurea* *Sphacelia segetum* [anamorph]
Eyespot	*Pseudocercosporella herpotrichoides* *Tapesia yallundae* [teleomorph]
Halo spot	*Pseudoseptoria donacis* *Selenophoma donacis*
Kernel blight = black point	*Alternaria* spp. *Arthrinium arundinis* *Apiosporam ontagnei* [teleomorph] *Cochliobolus sativus* Fusarium spp.
Ascochyta leaf spot	*Ascochyta hordei* *Ascochyta graminea* *Ascochyta sorghi* *Ascochyta tritici*
Net blotch	*Drechslera teres* *Pyrenophora teres* [teleomorph]
Net blotch (spot form)	*Drechslera teres* f. sp. *maculata*
Powdery mildew	*Erysiphe graminis* f. sp. *hordei* *Blumeria graminis* *Oidium monilioides* [anamorph]
Pythium root rot	*Pythium* spp. *Pythium arrhenomanes* *Pythium graminicola* *Pythium tardicrescens*
Rhizoctonia root rot	*Rhizoctonia solani* *Thanatephorus cucumeris* [teleomorph]
Rusts	
Crown rust	Puccinia coronata var. hordei
Leaf rust	*Puccinia hordei*
Stem rust	*Puccinia graminis* f. sp. *secalis* *Puccinia graminis* f. sp. *tritici*
Stripe rust = yellow rust	*Puccinia striiformis* f. sp. *hordei*
Scab = head blight	*Fusarium* spp. *Fusarium graminearum*
Scald	*Rhynchosporium secalis R. commune*
Septoria speckled leaf blotch	*Septoria passerinii* *Stagonospora avenae* f. sp. *triticae*

(continued)

Table 7.3 (continued)

Fungal diseases	Causal organism
Sharp eyespot	*Rhizoctonia cerealis* *Ceratobasidium cereale* [teleomorph]
Smuts	
Covered smut	*Ustilago hordei*
False loose smut	*Ustilago nigra* *Ustilago avenae*
Loose smut	*Ustilago nuda* *Ustilago tritici*
Snow molds	
Gray snow mold = Typhulablight	*Typhula incarnata* *Typhula ishikariensis*
Pink snow mold = Fusarium patch	*Microdochium nivale* *Fusarium nivale* *Monographella nivalis* [teleomorph]
Speckled snow mold	*Typhula idahoensis*
Snow rot	*Pythium iwayamae* *Pythium okanoganense* *Pythium paddicum*
Snow scald = Sclerotinia snow mold	*Myriosclerotinia borealis* *Sclerotinia borealis*
Southern blight	*Sclerotium rolfsii* *Athelia rolfsii* [teleomorph]
Spot blotch	*Bipolaris sorokiniana*
Spot blotch	*Cochliobolus sativus* *Drechslera teres* [anamorph]
Stagonospora blotch	*Stagonospora avenae* f. sp. *triticae* *Phaeosphaeria avenaria* f. sp. *triticae* [teleomorph],*Stagonospora nodorum* *Septoria nodorum* *Phaeosphaeria nodorum* [teleomorph]
Take-all	*Gaeumannomyces graminis* var *tritici*
Tan spot	*Pyrenophora tritici-repentis* *Pyrenophora trichostoma, Drechslera tritici-repentis* [anamorph] *Helminthosporium tritici-repentis*
Verticillium wilt	*Verticillium dahliae*
Wirrega blotch	*Drechslera wirreganensis*
Bacterial diseases	
Black chaff and bacterial streak	*Xanthomonas translucens* pv. *translucens*
Bacterial kernel blight	*Pseudomonas syringae* pv. *syringae*
Bacterial leaf blight	*Pseudomonas syringae* pv. *syringae*
Bacterial stripe	*Pseudomonas syringae* pv. *striafaciens*
Basal glume rot	*Pseudomonas syringae* pv. *atrofaciens*
Bacterial blight	*Xanthomonas campestris* pv. *translucens*
Anthracnose	*Colletotrichum cereale Manns*
Barley stripe	*Pyrenophora graminea* *Drechslera graminea*

(continued)

Table 7.3 (continued)

Fungal diseases	Causal organism
Nematode diseases	
Cereal cyst nematode	*Heterodera avenae* *Heterodera filipjevi* *Heterodera latipons*
Cereal root knot nematode	*Meloidogyne* spp. *Meloidogyne naasi* *Meloidogyne artiellia* *Meloidogyne chitwoodi*
Root gall nematode	*Subanguina radicicola*
Root lesion nematode	*Pratylenchus* spp.
Stunt nematode	*Merlinius brevidens* *Tylenchorhynchus dubius* *Tylenchorhynchus maximus*
Viral diseases	
African cereal streak	African cereal streak virus
Barley mild mosaic	Barley mild mosaic bymovirus (BaMMV)
Barley mosaic	Barley mosaic virus
Barley stripe mosaic	Barley stripe mosaic virus (BSMV)
Barley yellow dwarf	Barley yellow dwarf virus (BYDV)
Barley yellow streak mosaic	Barley yellow streak mosaic virus
Barley yellow stripe	Virus-like agent
Brome mosaic	Brome mosaic virus (BMV)
Cereal northern mosaic = barley yellow striate mosaic	Northern cereal mosaic virus (NCMV)
Cereal tillering	Cereal tillering disease virus (CTDV)
Chloris striate mosaic	Chloris striate mosaic virus (CSMV)
Eastern wheat striate	Eastern wheat striate virus
Enanismo	Virus-like agent
Hordeum mosaic	*Hordeum mosaic virus* (HoMV)
Oat blue dwarf	Oat blue dwarf virus (OBDV)
Oat pseudorosette	Oat pseudorosette virus
Oat sterile dwarf	Oat sterile dwarf virus (OSDV)
Rice black-streaked dwarf	Rice black-streaked dwarf virus (RBSDV)
Rice stripe	Rice stripe virus (RSV)
Russian winter wheat mosaic	Winter wheat Russian mosaic virus (WWRMV)
Wheat dwarf	Wheat dwarf virus (WDV)
Wheat soil-borne mosaic	Wheat soil-borne mosaic virus (SBWMV)
Wheat streak mosaic	Wheat streak mosaic virus (WSMV)
Wheat yellow leaf	Wheat yellow leaf virus (WYLV)
Aster yellows	Aster yellows phytoplasma

striiformis f. sp. *hordei*), leaf rust or brown rust (*Puccinia hordei*), stem rust or black rust (*Puccinia graminis*), spot blotch (*Bipolaris sorokiniana*/*Cochliobolus sativus*), powdery mildew (*Blumeria graminis* f. sp. *hordei*), net blotch (*Drechslera teres*/ *Pyrenophora teres*), stripe disease (*Drechslera graminea*), fusarium head blight (*F. graminearum, F. culmorum and F. crookwellense* covered smut (*Ustilago hordei*), loose smut (*Ustilago tritici*), bacterial streak (*Xanthomonas translucenspv. translucens*), barley yellow dwarf virus (BYDV) and cereal cyst nematode (*Heterodera avenae*) are major economically important diseases (Singh 2017; Verma et al. 2012a, b; Selvakumar 2012).

7.4.1 Foliar Diseases

Foliar diseases of barley are one of the main constraints to successful barley production. These diseases destroy green leaf area and, thus, restrict the barley plant's ability to set and fill grain. The main barley foliar diseases in India are rusts, powdery mildew, netted and spotted forms of net blotches, spot blotch and stripe disease (Singh et al. 2020). These diseases are considered economically very important because of their airborne nature, ability to spread widely and to cause epidemic.

7.4.1.1 Yellow Rust

Yellow rust of barley, caused by *Puccinia striiformis* Westend. f. sp. *hordei* Eriks. & Henn. (*Psh*), is an important disease of barley in India and several parts of the world (Safavi et al. 2012). It was first separated from other stripe rusts by Eriksson (1894). The *forma specialis* of this disease that affects primarily barley was found for the first time at Bogota, Colombia, in 1975 (Dubin and Stubbs 1986). Severe epidemics of the barley yellow rust have been reported in India, Bangladesh, Nepal, China, Japan and North-Western and Central European countries (Chen et al. 1995). Stripe rust is traditionally a disease of cool season and it appears earlier than other rust diseases (Mathre 1997). However, in recent years, stripe rust has emerged as serious threat in warmer areas where the disease was previously considered unimportant (Hovmoller et al. 2008; Milus et al. 2009). Stripe rust is a major biotic factor limiting barley production, especially in the cooler barley tracts of north-western plains and northern hills of India (Singh et al. 2016; Verma et al. 2018). It survives on Himalayan ranges and adjoining foothills. Sometimes it appears in traces in Bihar, eastern Uttar Pradesh and even Central India (Joshi 1978). In India, early incidence of stripe rust may create havoc in susceptible varieties, sometimes prevent ear head emergence or the grain formation resulting in heavy yield losses (Prakash and Verma 2009). In general, stripe rust is more destructive than stem and leaf rusts. It may cause up to 60% losses of yield in barley (Park et al. 2007). Yellow rust of barley caused yield losses of 15–20% during 1996 to 1999 in California (Chen 2007). In Iran, barley stripe rust was first reported in Iran in 1947 (Esfandiari 1947). Yield losses in barley due to stripe rust have been observed 14.25–24.55% in Ethiopia (Mulatu and Stefania 2011). Vais et al. (2011) reported 66% yield reduction in susceptible barley cultivars due to yellow rust in the trans-Himalayan region of India. In the epidemic years, it may implicit considerable losses due to premature death of foliage and sometimes by sterility of spikelet and shrivelling of grains. The G (4S0) was the first Indian *Psh* pathotype detected from Nilgiris hills, Tamilnadu in 1939.

7.4.1.2 Symptoms

Initial symptoms include chlorotic flecks at the site of infection (Fig. 7.3a). Orange-yellow uredo-pustules contain uredospores that appear in the form of narrow, linear stripes on leaf, sheaths, neck and glumes (Fig. 7.3b). The stripe rust is unique because individual uredia spread in a line from the site of initial infection. As the disease progresses, the stripes continue to enlarge as the fungus is partially systemic. Stripe rust is principally a disease of barley in cooler climates (11–15 °C) and free moisture (mediated by rainfall or dew), which provide optimal conditions for infection (Stubbs 1985; Roelfs et al. 1992). In conducive conditions, pustules erupt within 8–14 days after infection and freshly released uredospores become airborne which facilitate secondary infection and faster disease development (Prashar et al. 2015). The uredospores initiate germination at 9–15 °C with free water and growth of germ tube takes place at 10–15 °C. An optimal temperature 8–13 °C favours formation of appressorium and sub-stomata vesicle under humid conditions (Gangwar et al. 2018). Stripe rust symptoms usually appear earlier in the season than stem and leaf rusts. The rusted plants are stunted and they produce small spike in extreme disease situation (Fig. 7.4a).

There is impairment of fertility of florets to reduce the number of seed set per head (Srivastava 2010). Severe infection results in premature drying of the plants. Thus, the major cause of loss in barley yield is on account of producing shrivelled seed with reduced size and grain weight (Fig. 7.5a). Damage to barley depends on the growth stage. It has been noticed that early infection of rust in barley causing maximum damage. The urediospores loose viability rapidly at temperature above 15 °C. Disease development is more rapid when temperature is between 10 and 15 °C and intermittent rain or dew is present. Black telia readily develop from uredia as infected barley plants approach maturity (Fig. 7.4b).

The teliosori are arranged in long stripe and covered by epidermis. The uredio and teliospore stages of *P. striiformis* f. sp. *hordei* occur on barley and various *Hordeum* species (Marshall and Sutton 1995). The pycnial and aecial spore stages of *Psh* are not documented so far. Volunteer plants, autumn sown barley crops and wild *Hordeum* species can serve as inoculum reservoirs for barley yellow rust (Dubin and Stubbs 1986; Marshall and Sutton 1995).

7.4.1.3 Disease Cycle

In India, stripe rust can exist independent of an alternate host. The pathogen over-summers under cool climate in the inner valley of Himalayas on barley and on volunteer plants in uredial stage. When favourable temperature returns, the sori of rust bust into uredia with abundant uredospores and the inoculums move towards foothills of Northern India. By December/January when the crop is about a month

Fig. 7.3 (**a**) Initial chlorotic flecking; (**b**) Stripe rust symptoms on barley crop

A)

B)

old, the inoculum then spreads by katabatic winds to sub-mountainous parts of north-western plain zone. Primary infection foci occur in this region along the mouth of rivers, namely Tavi, Ravi, Beas, Satluj and Yamuna. Later on, the katabatic winds carry the uredospores to adjoining plains and cause infection (Srivastava 2010). The pathogen infecting a leaf remains partially systemic within that leaf, and thereafter, several uredo cycles on infected plants result in high disease severity. At maturity of the crop, the temperature begins to rise and it is not congenial for

Fig. 7.4 (**a**) Severe stripe rust infection on barley; (**b**) Telial stage of stripe rust on barley crop

A)

B)

uredospore production. The spread of the rust is checked above 25 °C. With the ceasing of sporulation, the telial stage develops (Fig. 7.6b). The teliospores apparently serve no function in the absence of alternate host and recurrence of the disease takes place through air-borne uredospores from primary foci of infection. The physiological races of *P. striiformis* f. sp. *hordei* recorded in India are 0S0–1 (24), 0S0 (57), 1S0 (M), 4S0 (G), 4S0–3(G-1), 4S0–3(G-1) and 5S0 (Q). However, the

Fig. 7.5 (**a**) Shrivelled grains from stripe rust-infected ears (**b**) healthy seed

pathotype 1S0 (M) has been found predominate for the last 70 years followed by pathotypes, 24, 57 and G (Fig. 7.6).

7.4.1.4 Leaf Rust

The leaf rust caused by the fungus *Puccinia hordei* G. Otth. is a common disease of barley and has been reported in most production region across the world including Australia, Europe, North America, South America and Indian sub-continents where climate is little warmer (Niekerk et al. 2001; Verma 2018). Yield losses of 26–31%

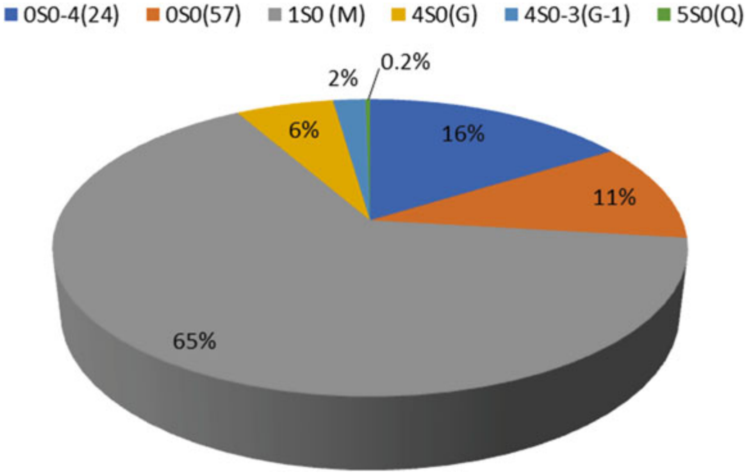

Fig. 7.6 Pathotypes spectrum of stripe rust of barley in India during 2003–2004 to 2019–2020

was reported in Australia during a moderate-to-severe epidemic in 1990 (Cotterill et al. 1992). In India, leaf rust is the most common disease prevalent in north-western and north-eastern, central and peninsular regions. Although, brown rust occurs in all the barley growing areas of India, this pathogen seldom causes severe epidemics over a wide area. Still, significant yield losses can occur in susceptible cultivars when the inoculum arrives early and levels are high. Under experimental conditions, over 60% yield losses were reported in highly susceptible barley cultivars (Das et al. 2007).

Symptoms

Brown rust appears as small, circular, orange-brown, uredial pustules scattered mainly on upper surface of leaf blade and, in case of severe infection under high inoculum load, symptoms may also appear on stems, leaf sheath, peduncles, internodes, ear heads, glumes and awns (Fig. 7.7). The pustules erupt from the infected part and the uredospores spread by wind to other leaves. Heavily infected leaves die prematurely. Later in the season, telia are formed on stems, heads and leaf blades as blackish brown, usually in stripes covered by the epidermis (Park et al. 2015).

Disease Cycle

Leaf rust of barley is macro-cyclic rust. In the absence of alternate hosts, the pathogen perpetuates in the form of uredial stage on self-sown barley plants and collateral hosts in both Himalayas and South Indian hills. The rust inoculum in the form of uredospores spreads from hilly region into plains where they cause infection on regular barley crop. Uredospores are wind-borne and can spread long distances. A temperature ranging from 20 to 25 °C and prolonged wet weather are prerequisite for faster spread of the disease. Under such conditions, new uredia are generally formed

Fig. 7.7 Leaf rust infection on barley in the field

within 7–10 days after infection and the cycle of spore production is repeated (Gangwar et al. 2018). Teliospores develop later in the season either within uredial sori or within separate telial sori. The uredial and telial spore stages of leaf rust pathogen occur on barley and various wild *Hordeum* spp., and the pycnial and aecial spore stages have been reported on alternate hosts of the Liliaceae family, such as *Ornithogalum*, *Leopoldia* and *Dipcadi* (Clifford 1985). In India, where rust cannot over-winter and alternate host is not present, the fungus is reintroduced annually through uredospores called repeating spores. The uredospores are repeatedly reproduced asexually on barley plants during crop season. The pathotypes of leaf rusts prevailing in India are H_1, H_2, H_3, H_4 and H5 (Bhardwaj and Gangwar 2012).

7.4.1.5 Stem Rust

The stem rust caused by obligate biotrophic fungus, *Puccinia graminis* Pers. f. sp. *tritici* Eriks. & Henn. (*Pgt*) and *Puccinia graminis* Pers. f. sp. *secalis* Eriks. & Henn. (*Pgs*), is a serious disease of barley. It is primarily a warm weather disease, but it can cause great damage to susceptible barley crops over broad geographical regions (Leonard and Szabo 2005). Historically, stem rust epidemics had caused devastating yield losses of barley in several parts of the world, including the northern Great Plains of the United States (Roelfs et al. 1992; Steffenson 1992). This area is known as stem rust-prone area that regularly suffer stem rust epidemics in barley prior to the 1940s (Steffenson 1992). In the twentieth century, the most severe stem rust epidemic in Europe occurred in 1932 and 1951 (Zadoks 1963). The barley variety Kindred was released as the first commercial barley containing the stem rust resistance gene Rpg^1 (Steffenson 1992). A new race of Pgt designated as QCCJB was identified in North Dakota that was virulent on barley cultivars carrying RPG^1 (Roelfs et al. 1992). The Pgt race QCCJB became the most prevalent race in

Northern USA and threatened commercial barley varieties (Roelfs et al. 1992). Jin et al. (1994) identified a gene designated as rpg[4] from an unimproved barley line Q21861 conferring resistance to Pgt race QCCJB. A new highly virulent Pgt race TTKSK (Ug99) and its lineage pose an alarming threat to global wheat and barley production and global food security (Steffenson and Jin 2006; Singh et al. 2010; Steffenson et al. 2017). Race TTKSK was first reported in 1999 from wheat fields in Uganda, Africa (Pretorius et al. 2000). Steffenson et al. (2017) reported that 96% of 2913 barley accessions, including those containing RPg1, were extremely vulnerable to this evolving Pgt race. In India, stem rust is primarily a disease of the Central and Peninsular zones. The uredospores of stem rust never arrive in time from central zone to northern region, so the disease appears late in this part and usually does not cause much damage. Isolated but severe epidemics of stem and leaf rusts were recorded in district Jalore of Rajasthan in 1973. The yield losses implicated by stem rust have been enormous in stem rust-prone areas of the country.

Symptoms

The dark reddish-brown, elongated large uredial pustules appear predominantly on the stem and leaf sheaths but under severe infection pustules can form on the leaf blades, glumes and awns. Initially, the pustules are scattered but later they may coalesce. The uredia tear the affected stem and leaf tissue, giving a distinctly tattered appearance on the margins of the pustule, a most characteristic feature of stem rust (Fig. 7.8). Severe infections with many stem lesions may weaken plant stems and result in breaking of stem from the severe infection point. Late in the season, rust coloured pustules turn into black telia containing teliospores (Bhardwaj et al. 2017). The telia are conspicuous, linear, oblong, dark to black and often merge with one another to cause linear patches of black lesions.

Puccinia tritici is a macro-cyclic, heteroecious fungus. The pycnial-spore and aecial-spore stages occur on *Berberis* spp. and *Mahonia* spp., which act as alternate hosts. The alternate host species of *Berberis* and *Mahonia* can provide a source of primary inoculum in the form of aeciospores, although this spore is generally disseminated over short distances (Roelfs et al 1992). Since under Indian conditions the functional alternate hosts (susceptible *Berberis* and *Mahonia* spp.) are absent, the uredospores surviving on volunteer plants, summer crop or some other grasses/ plants on the Nilgiris hills play a major role in the survival and perpetuation of the fungus and act as a primary source of inoculum (Bhardwaj et al. 2016). North Indian hills do not play any role in the epidemiology of barley black rust in India.

Disease Cycle

Under Indian conditions, role of alternate hosts is not functional, and no pycnial and aecial stages of *Pg* have been discovered. The teliospores are not capable of immediate germination under hot and dry conditions of summer season (Mehta 1940). Thus, the survival of the stem rust in the Indian sub-continent is only through uredospores which are produced on collateral hosts, namely volunteer wheat, barley, triticale and some grasses at high altitudes on the hills. These plants can become heavily infected with stem rust in the autumn, and become a source of primary

Fig. 7.8 Stem rust pustules on barley

inoculum of rust for the new season barley crop. The disease is favoured by warm, moist weather. The optimal conditions for infection are a temperature range of 15–28 °C and 6–8 h of free moisture on the leaf surface. Disease spreads rapidly if wet weather persists and temperature remained in the range of 26–30 °C. Several cycles of uredospore production occur during the growing season. Physiological races of *P. graminis* recorded in India are 79G31(11), 62G29 (40A), 37G19 (117–6), 75G5 (21A- 2) and 7G43(295).

Epidemiology of Rusts in India

The rust pathogens of wheat and barley are devastating as they evolve continuously, and their uredospores spread by air over a long distance. Under Indian conditions (Bhardwaj et al. 2017), alternate hosts do not play any role in the perpetuation of rust pathogens under Indian conditions. In India, the rust pathogens are believed to survive and perpetuate on self-sown wheat and barley plants, summer crop of hills, volunteer plants of wheat and barley and many collateral hosts such as *Aegilops squarrosa*, *A. ventricosa*, *A. trinecilis*, *Bromus carinatus*, *B. coloratus*, *B. japonicas*, *B. mollis*, *B. patulus*, *Hilaria jamesii*, *Hordeum distichum*, *H. murinum, H. stenostachys* and *Lolium perenne* also serve as off-season hosts in the annual recurrence of the stem rust fungus (Bhardwaj et al. 2017).

Stripe Rust

Stripe rust pathogen prefers low temperature for infection and symptoms expression so it survives in uredial form at several locations in Himalayan ranges in the absence of alternate host (Mehta 1940). By December/January, when the crop is about a month old, the rust appears along the hills of northern hill zone/north-western plains zone along the mouth of rivers such as Tawi, Ravi, Beas, Sutlej and Yamuna, where temperatures are low and dew is abundant (Nagarajan et al. 2006). The disease can survive in Nilgiri and Pulney hills but it cannot spread even to the foothills of Nilgiris due to unfavourable warm weather (Joshi et al. 1984). Hence, this disease is essentially a major problem of north and north-western regions of the country.

Leaf Rust

Leaf rust of wheat spreads both from South and North Indian hills (Mehta 1940; Mehta 1952). This view is supported by recent studies. It has been demonstrated that the first built-up of leaf rust like stem rust takes place in plains of Karnataka in South India, generally in the last week of December. At the same time, the infection also establishes in Bihar in north-eastern region of the country. The rust population from southern region moves north towards Maharashtra and Madhya Pradesh and population moves from northern region towards south. Finally, both the populations, moving in opposite direction, merge into each other (Joshi et al. 1974). Nagarajan et al. (1979) explored that the uredospores of leaf rust from northern region are also carried away by western disturbance. This observation suggests that if more western disturbances accompanied by frequent rains occur in North India, there is apparently good chance for the spread and built-up of leaf rust in north-western region to lead to an epidemic.

Stem Rust

Stem rust uredospores spread primarily from Nilgiri and Pulney hills and Himalayas play a minor role in recurrence of epidemics of the disease in Northern India (Joshi et al. 1974). The sporulation of stem rust over naturally infected fields in southern hills is faster under warm weather. Hence, many places in southern peninsular India get early outbreaks of stem rust in December and January. In contrast, low temperature prevailing in Himalayan region during winter months hamper the sporulation and multiplication of *P. graminis* (Srivastava 2010). The South Indian hills are considered the main foci of stem rust infection in India (Joshi 1976). Spread of stem rust from Central India to other parts of Northern India is favoured by the repeated passage of western disturbance, linking both areas. The associated winter precipitation permits countrywide spread of stem rust (Bhardwaj et al. 2010).

Integrated Management Rusts

Resistant Varieties

Use of resistant varieties is an eco-friendly, sustainable, practically feasible approach for the management of rust diseases. The development of high-yielding rust-resistant varieties for different traits is the main objective of All India Barley Network Project.

The important rust-resistant barley varieties developed for different traits for the cultivation in different production situations released by CVRC are given in Table 7.4 (Kumar et al. 2017).

The barley genotypes, DWRB127, DWRB137, DWRB 143, RD2552, RD 2786 and Dolma (Kumar et al. 2020) and DWRFB12, DWRFB 14, DWRFB 19 and DWRFB 20 (Singh et al. 2019), were identified as highly resistant to yellow rust when tested both at seedling and adult plant stages. Similarly, exotic barley genotypes, namely ARAMIR/COSSACK, Astrix, C8806, C9430, CLE202, Gold, Gull, Isaria, Lechtaler, Piroline, Stirling and Trumpf (Verma et al. 2018) and AM14, AM36, AM37, AM103, AM120, AM177, AM189, AM274, AM275, AM291 and AM300 (Gyawali et al. 2018) showed resistant to all the six Indian pathotypes *Psh* at both seedling and adult plant stages. The barley genotypes DWRB152, DWRB137, HBL 822, PL900, RD2973, RD2976, UPB1070 and VLB130 were found highly resistant to yellow (ICAR-IIWBR 2019). Genotypes BH1024, KB1762 and RD3008 were found resistant to all three rusts, whereas BHS 474, HBL845, HBL863, RD2786, RD2991 and RD3003 were found resistant to both leaf and stripe rust (ICAR-IIWBR 2019). These identified resistant sources from indigenous and exotic gene pool may be utilized as donor in future barley breeding programme for developing high-yielding, rust-resistant varieties.

Balanced Crop Nutrition

Application of balance fertilizer meets the macro- and micro-nutrients need of the crops which promote healthy root system and more vigorous growth. Usually, a vigorous growing crop has the ability to tolerate disease. Application of a balanced crop nutrition, especially nitrogen and potassium is helpful in protecting crop from the biotic and abiotic stresses. Excess nitrogenous fertilizers provide better condition for the development of rusts in barley crop.

Crop Health Monitoring

Effective disease management relies on accurate identification of disease and their causal agent through regular systemic inspection of a growing crop during the season. Crop health monitoring and surveillance is necessary to keep a vigil on the occurrence of disease and evolving new races, especially in targeted areas. Fungicides are more effective as protectants than eradicates, when applied before or at the initiation of disease to avoid crop losses.

Fungicides

Use of suitable fungicide under rust epidemic situations is the only option in reducing rust severity as a component of integrated disease management. The foliar spray of propiconazole 25EC @ 0.1% reduced the incidence of barley rust (Singh et al. 2010; Devlash et al. 2015). Selvakumar et al. (2014) observed that foliar spray of Tebuconazole 25.9%EC@0.1% was the best for rust control in barley. Similarly, Kanwar et al. (2018) reported that yellow rust of barley can be effectively controlled by the foliar spray of Trifloxystrobin 25% + Tebuconazole 50% (75WG) @ 0.1%.

Table 7.4 Rust-resistant barley varieties for different production conditions in India

Variety	Cross/parentage	Year of release	Released for	Salient features
RD 2552	RD2035/DL472	2000	NWPZ and NEPZ for irrigated, timely sown	High-yielding feed barley
RD 2624	Bilara2/RD2508	2004	NWPZ for rain fed timely sowing	Feed barley for rainfed areas
RD 2660	RD2052/RD 2566	2006	NWPZ under rain fed	Feed barley for rain-fed areas
RD 2668	RD2035/BCU73	2007	Irrigated timely sowing in NWPZ	Two-rowed malt barley
RD 2715	RD387/BH602// RD2035	2009	Irrigated, timely sown in central zone (CZ)	Dual purpose barley for feed and forage
RD 2786	RD2634/NDB1020// K425	2013	Irrigated, timely sown in CZ	Feed barley
RD 2794	RD2035/RD2683	2016	Irrigated, timely sown in NWPZ and NEPZ under saline/sodic soils	Feed barley for salt affected areas
RD 2849	DWRUB52/PL705	2016	Irrigated, timely sown in NWPZ	Two rowed malt barley
RD 2907	RD103/RD2518// RD2592	2019	Irrigated, timely sown in NWPZ and NEPZ under saline/sodic soils	Feed barley for salt affected areas
RD 2899	RD2592/RD2035// RD2715	2019	Irrigated, timely sown in CZ	Feed barley
DWRUB 52	DWR17/K551	2007	Irrigated, timely sown in NWPZ	Two-rowed malt barley
DWRB 73	PL710/DWR17	2011	Irrigated, late sown in NWPZ	Two-rowed malt barley
DWRUB 64	DL472/PL705	2012	Irrigated, late sown in NWPZ	Six-rowed malt barley
DWRB 91	DWR46/RD2552	2013	Irrigated, late sown in NWPZ	Two-rowed malt barley
DWRB 92	DWR28/DWR45	2014	Irrigated, timely sown in NWPZ	Two-rowed malt barley
DWRB 101	DWR28/BH581	2015	Irrigated, timely sown in NWPZ	Two-rowed malt barley
DWRB 123	DWRUB54/DWR51	2017	Irrigated, timely sown in NWPZ	Two-rowed malt barley
BH 902	BH495/RD2552	2010	Irrigated, timely sown in NWPZ	Feed barley
BH 946	BHMS22A/BH549// RD2552	2014	Irrigated, timely sown in NWPZ	Feed barley
BH 959	BH393/BH331	2015	Irrigated, timely sown in CZ	Feed barley
PL751	K226/PL226	2007	Irrigated, timely sown in CZ	Feed barley
UPB 1008	HIGO/LINO/3/ CHANICO/	2011	Rain fed, timely sown in NHZ	Two-rowed feed barley

(continued)

Table 7.4 (continued)

Variety	Cross/parentage	Year of release	Released for	Salient features
	TOCTE// CONGONA/4/			
HUB 113	Karan280/C138	2014	Irrigated, timely sown in NWPZ	Feed barley
BHS 352	HBL240/BHS504// VLB129	2003	Rain fed, timely sown in NHZ	Hulless feed barley
BHS 400	34th IBON9009	2014	Rain fed, timely sown in NHZ	Six rowed feed barley

7.4.1.6 Stripe Disease

Stripe disease caused by *Drechslera graminea* (Rabenh.) Shoemaker (formerly *Helminthosporium gramineum*) is a worldwide occurrence with considerable damage to the barley crop from seedling to maturity. The disease reduces the yield and quality of barley and causes economically important yield losses in many countries. Yield losses from 3.3 to 15% have been reported in infected spikes. Yield losses up to 73% have also been reported in susceptible barley cultivars (Mathur and Bhatnagar 1991; Arabi et al. 2004).

Symptoms

The first symptoms appear as small pale-coloured spots on lower leaves and sheaths of seedling plants (Fig. 7.9). These spots fuse together and form long, parallel, brownish stripes. These stripes are continuous from the base to the tip of the leaf. The infection is systemic and symptoms can be seen on all the tillers and leaves of a plant.

The yellow stripes soon become brown as tissue necrosis progresses and, finally, the tissues dry out and the leaf blade shreds (leaf shredding). The spikes are blighted, twisted, compressed and brown in colour. Infected plants are stunted, produce sterile spikes and die prematurely. A grey to olive grey mass of conidiophores and conidia of the fungus *Drechslera graminea* develop on lesions (Fig. 7.10).

Disease Cycle

The pathogen is seed- and soil-borne in nature. It survives through mycelium in seed and in crop debris lying in the soil. The infection is systemic. Primary infection is caused by hyphae that penetrate through the coleoptiles, coleorhizae or root and grow upward through the seedling. Abundant conidia are produced on infected leaves during periods of high humidity. The conidia are windblown to nearby plants where they lodge on flowers and infect seeds at kernel development stage (for seed-borne nature). Secondary infection occurs by means of conidia formed on conidiophores after primary infection of the crop. The pathogen remains dormant as mycelium on or within the dry barley grains until the seed germinates. The stripe fungus then resumes active growth, progressing into the sheath surrounding the first

A)

B)

Fig. 7.9 (**a** and **b**) Initial symptoms of stripe disease on barley seedlings

seedling leaf, from that into the next leaf and continuing until all of the leaves are infected. The spores of the stripe pathogen can remain alive for as long as 34 months. Most favourable condition is heavy dew or rainfall during flowering. Low soil temperature (around 12 °C) and moderate soil moisture are favourable for systemic invasion. Infection greatly reduces at soil temperature above 15°C. Cool, moist and fertile soil also enhances the disease in seedlings. Disease is favoured by deep sowing, that is, 4–5 cm, while it is less favoured at 2–3 cm depth. Infection can occur at temperatures ranging from 10 to 33 °C.

Management

- Barley cultivars RD 2660, RD 2849, RD 2786, RD 2668, RD 2715 and RD 2592 were found moderately resistant to stripe disease (Kumar et al. 2019a, b).
- Use only thoroughly cleaned, certified barley seed from disease-free fields.
- Maintain good farm hygiene by minimizing the movement of pathogen on farm and between the fields through clean farm machinery and vehicle.

Fig. 7.10 (**a**) Stripe disease infection on barley; (**b**) Stripe disease in farmer's field

A)

B)

- Plough under crop residues deep and clean as soon as possible after harvest.
- Keep down susceptible grasses and volunteer small grain hosts by cultural or chemical means.
- An effective and intergrated weed control program should be followed to reduce the amount of pathogen inoculum from the field that could move into healthy plant parts.
- Rotate small grains and grasses with non-host crops, preferably with legumes.
- Produce seed in dry areas.
- Adopt shallow sowing (2–3 cm depth).

- Maintain appropriate crop geometry as dense canopy favours disease development.
- Treat the seeds with Tebuconazole 2% DS or Carboxin +Thiram (1:1) 75%WP @ 0.2% (Kumar et al. 2019a, b).

7.4.1.7 Powdery Mildew

Powdery mildew is a widely distributed disease of barley in humid and sub-humid regions of the world. It is caused by the ascomycetous fungus *Blumeria graminis* (DC.) Speer f. sp. *hordei* Marchal, which has *Oidium monilioides* as the anamorph stage (Mathre 1997; Braun et al. 2002). Generally, the disease is favoured by cool and humid weather but can also occur in warmer, semiarid environments (Mathre 1997). Losses exceeding 14% can occur when disease onset is early and inoculum pressure is high. The pathogen can infect barley without the presence of free moisture. The *B. graminis* f. sp. *hordei* is composed of many races and their population dynamic can rapidly change to overcome resistant genes in the host (Brown 1994; Wolfe and McDermott 1994). Mutation and genetic recombination via the sexual stage are the main factors contributing to new virulence types of the pathogen. Bahadur and Aggarwal (1997) recorded 41 pathotypes from Himachal Pradesh, Haryana and western Uttar Pradesh and 21 from Nilgiri hills in South India. In India, the disease is mainly confined to northern and southern hills (Misra et al. 2005).

Symptoms

Initial symptoms appear as fuzzy, whitish tufts of fungal mycelium on leaf blade. Later, powdery or fluffy white pustules of conidial chains develop from the mycelium which may turn grey or slightly brownish with age (Fig. 7.11a) (Kiesling 1985).

All aboveground part can be affected. The underside of the infected leaves has yellowish necrotic spots at the infection sites. Late in the growing season, small globose-shaped dot-like black spore cases (cleistothecia) of the fungus may be found embedded in the mildew pustules usually towards the end of the season (Fig. 7.11b). The affected leaves may crinkle, twist or deform under severe infection. In case of severe infection, free water inhibits spore germination. Under favourable conditions, the disease spreads fast and the symptoms appear on leaf sheaths and spikes, resulting in premature dying of the leaves and ear head emergence may get adversely affected. The disease perpetuates on volunteers and grasses from one season to the next season.

Disease Cycle

The powdery mildew fungus is a biotrophic pathogen. During crop season, the ascospores released from cleistothecium bring about primary infection on plant leaves. These lesions produce conidia in abundance within a short period, which causes secondary infection in the foot hills and adjoining plains. Germ tubes from both conidia and ascospores can penetrate the host cuticle directly. The conidia can easily disseminate by wind to infect barley. At maturity of the crop, the fungus produces cleistothecia, which remain on plant debris and act as a source of primary

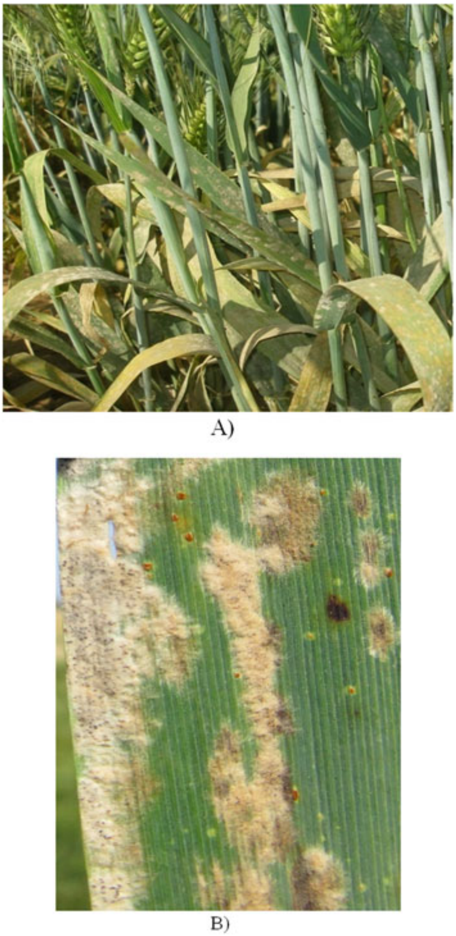

Fig. 7.11 (**a**) Powdery mildew infection on barley; (**b**) clesitothesia on barley leaf

inoculum for the next crop season. The cleistothecia serves as a survival stage for pathogen and produces sexually derived ascospores, which are discharged from asci to infect the new barley crop. Secondary cycles of infection occur by conidia produced in massive numbers from severely infected crop. Conidia can travel over hundreds of miles to infect crops and are the most important propagules in the epidemiology of the disease (Wolfe and McDermott 1994). Powdery mildew development is optimal between 20 and 22 °C with a relative humidity between 24 and 75% and is markedly retarded above 30 °C (Timothy and Brain 2010).

Management

Cultural Practices

Deep summer ploughing and burning of diseased plant debris to eliminate the primary source of inoculum; judicious use of nitrogenous fertilizers; timely sowing, proper crop geometry and well-drained soil help in reducing the disease severity (Singh and Srivastava 1992).

Fungicide

The disease can be controlled through spray of Propiconazole 25EC @ 0.1% (Singh 2008).

7.4.1.8 Net Blotch

Net blotch is an important and common disease in almost every barley production region of the world. The disease is named for the characteristic cross-hatch pattern of dark-brown striation that develop within lesion (Shipton et al. 1973). The disease occurs in two forms, that is, net form (NFNB) and spot form of net blotch (SFNB). The causal agents of net and spot blotch are morphologically similar but produce different types of symptoms. *Pyrenophora teres* f. *teres* is the causal organism of NFNB that produces typical net-type lesions and P. teres f. maculate, the causal agent of SFNB with elliptical lesions.

Symptoms

Net blotch is mainly a disease of the leaves but some time symptoms appear on leaf sheaths, stems and kernels also (McLean et al. 2009). Initial symptoms of NFNB begin as a small pinpoint to elliptical brown spots, which expand to form narrow, tan to light brown lesions, often delimited by leaf veins. Within these lesions, dark brown longitudinal and transverse striations appear, forming a net-like pattern (Fig. 7.12a). Chlorosis may surround the necrotic lesions in susceptible genotypes. The initial symptoms of SFNB are very similar to those of NFNB (McLean et al. 2009). The spot form of net blotch symptoms appear as dark brown, circular-to-elliptical lesions surrounded by bands of chlorosis. The symptoms produced by both forms of net blotch can vary greatly depending on the isolate of the pathogen, genotype and growth stage of the host and environment (McLean et al. 2009). Net blotch has the potential to cause total loss in susceptible cultivars under conducive environmental conditions (Mathre 1997).

7.4.1.9 Spot Blotch

Spot blotch of barley caused by *Cochliobolus sativus* {(Ito & Kurib.) Drechsl. ex Dast. [anamorph: *Bipolaris sorokiniana* (Sacc. in Sorok.) Shoem.]}, is a serious foliar disease. Spot blotch is one of the major diseases of wheat and barley in warm and humid regions (Kuldeep et al. 2008). The pathogen is a hemibiotrophic fungus and reported to cause foliar blight, spot blotch, leaf spot, seedling blight, head blight, black point of grain in barley (Kumar et al. 2002). The disease is distributed in most barley production regions of the world and is important in Africa, South America, Australia, Canada, Asia and particularly Indian sub-continent having warm and humid environment (Singh and Srivastava 1997). In India, the disease appears in severe form in Bihar, West Bengal, eastern Uttar Pradesh, Orissa and Tamil Nadu. With recent changes in cropping pattern leading to delayed sowing of barley in rice belt of Punjab, Haryana and western Uttar Pradesh as well as climate change,

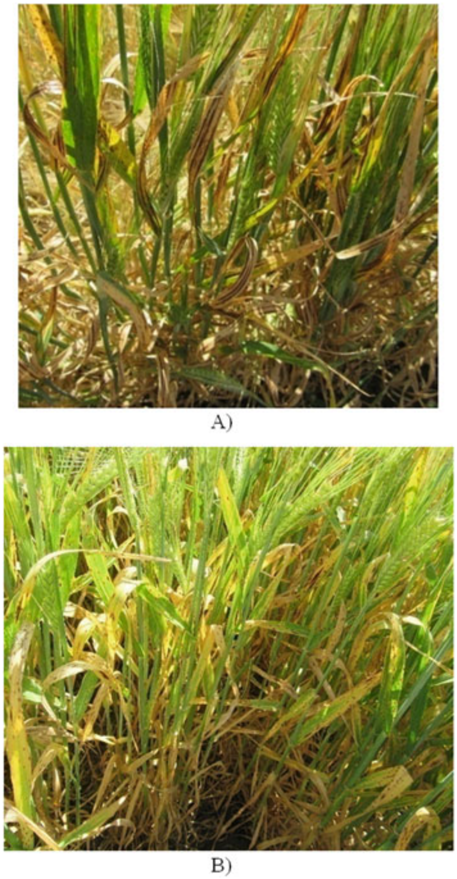

Fig. 7.12 (**a**) Net form of net blotch on barley; (**b**) Spot form of net blotch on barley

particularly sudden rise in temperature in the month of February with intermittent rainfall, create congenial conditions for the disease. At present, lack of resistance in most of the popular barley cultivars against spot blotch disease has emerged as one of the major constraint (Singh 2004b; Aggarwal 2009). Jaysana et al. (2007) reported 23–44% yield loss by spot blotch besides causing deterioration in grain quality.

Symptoms

Spot blotch occurs primarily on the leaves and leaf sheaths of barley but under severe infection, symptoms may appear in other plant parts including internodes, stem, nodes, awn, glumes and seed. Early lesions on the leaves are characterized by pinpoint small, dark-brown lesions 1–2 mm long without chlorotic margin, which extend to oval-to-elongated blotches, light brown to dark brown in colour giving a blighted look (Fig. 7.13a). Pathogen signs of conidia and conidiophores in form of "dusty specks" can sometimes be observed in older lesion, visible to the naked eye (Fig. 7.13b). Root and crown infections in severe form may lead to complete drying

Fig. 7.13 (**a**) Typical symptoms of spot blotch in barley; (**b**) spot blotch infection in infected barley crop

(A)

(B)

of infected plants without seed production (Zillinsky 1983). If moist conditions prevail late into the season, infection can occur as dark-brown lesions on basal end of the kernels, which is known as black point or kernel blight phase (Mathre 1997). It displays an early biotrophic phase when the hyphae penetrate the cuticle and cell wall and begin to grow inside living epidermis cells. Subsequently, hyphae will ramify in dead epidermis and mesophyll cells as the pathogen assumes its necrotrophic phase (Kumar et al. 2002).

Disease Cycle

The spot blotch pathogen, *B. sorokiniana* survives in infected seed, infected crop residues, volunteer plants and free dormant conidia in the soil serve as primary source of inocula (Aggarwal 2009). Inoculum in infected plant debris in the form of conidia can be readily dispersed by wind, which is most important for initiating spot blotch epidemic. The pathogen has an extremely wide host range that even includes dicotyledons hosts (Tinline 1988). These alternate hosts may also act as a primary source of inoculum. Multiple cycles of secondary infection occur through conidia produced in primary infection on the foliage of barley. The pathogen is favoured by moderate-to-warm temperatures (18–32 °C) with humid weather (Singh and Srivastava 1997).

Management

The basic principle involved in the management of *B. sorokiniana* is reducing the inoculum source.

Deep Summer Ploughing and Crop Residue Management

Deep summer ploughing and destruction of infected barley crop debris is often suggested as means to reduce primary source of inoculum.

Crop Rotation

Diversification of crops in a rotation helps to break-up the life cycles of many pathogens. Rotation act as natural soil fumigation because the collective activity of antibiotic, predatory and competitive organisms helps to reduce inoculum present in the soil. Crop rotation with non-host crops such as oats, rye and broad leaf species helps in elimination of the soil-borne inoculum of barley leaf spot pathogen (Selvakumar 2012).

Varietal Choice

Always choose the quality seed of resistant variety recommended for the cultivation in particular areas. Barley cultivars K551, K560, DL88, RD2552, NDB 1173, DWRUB 52, DWRB 73, DWRUB 64, HUB 113, DWRB 101and DWRB 123 are found resistant to spot blotch disease (Kumar et al. 2017). Singh et al. (2014) reported that barley genotypes BCU422, BCU1204 and BCU5092 were found resistant to *B. sorokiniana.* Barley genotypes BH 1011, BH1018, BK1719, BK1723, DWRB178, KB1633, PL890, PL900, Pl902 and UPB1071 were found resistant to spot blotch of barley (ICAR-IIWBR 2019).

Seed Treatment

Seed treatment with carboxin 75%WP or Captan @3 g or *Trichoderma viride* @ 4/Kg seed was found effective to eliminate the seed-borne inoculum of *B. sorokiniana*. Moreover, treated seed with shallow placement always reduces the risk of seedling blight because deep seeding results in additional energy and time being expended by the emerging seedling to reach the soil surface, thus, weakening it and making it more vulnerable to attack by soil-borne pathogen, Sowing Time

Avoid late planting so that crop does not coincide with hot and humid period congenial for spreading the barley leaf spot disease. It has been observed that disease in late sown crop progresses at higher rate than normal sowing in north-eastern region of India.

Biocontrol

Foliar spray with *Chaetomium globosum* strain Cg-2 @10^6cfu/mL is effective in controlling the spot blotch disease (Aggarwal et al., 2004). Seed and soil application of *Trichoderma viride* was found effective against spot blotch of barley (Singh et al. 2018; Pande et al. 2019).

Fungicide

Singh (2008) reported that spraying of porpiconazole 25 EC @ 0.750 l/ha at booting and soft dough stages proved most economical in controlling the foliar blight disease. Seed treatment with Carboxin 75 WP @ 2.5 g/kg seed + two foliar sprays of propiconazole @ 0.1%, first at boot leaf stage and second after 20 days, proved best to control blight in barley (Kumar et al. 2018).

7.4.1.10 Barley Yellow Dwarf

Barley yellow dwarf caused by Barley yellow dwarf virus (BYDV) is a globally distributed important viral disease complex that affects barley, wheat and oat (Bockus et al., 2010). BYD is caused by up to ten related phloem-limited strains or species, which are collectively referred to as barley yellow dwarf viruses (BYDVs) (Murray et al. 2015). This virus is transmitted by the several species of grass feeding aphids (Whitworth and Ahmad 2008). Aphid infestation and viral infection disrupt phloem transport of photosynthesized assimilates in BYDV-infected barley plants (Botha and Matsiliza 2004). Yield losses attributable to BYDVs may vary with the strain of the virus, cultivar, growth stage at infection and environmental factors (Perry et al. 2000). Losses in yield can be about 66% at 100% BYD incidence (Peiris et al. 2019).

7.4.1.11 Symptoms

BYDV infection causes stunting, progressive yellow or purple leaf discolouration starting from the leaf tips, small black spots on leaf tips, shrivelled kernels and darkened heads at maturity (Bockus et al. 2010; Bockus et al. 2016). The disease appears initially confined to single plants scattered in random patterns in the field but later develops into circular patches as secondary spread occurs (Gangwar et al. 2018; Peiris et al. 2019).

7.4.2 Smut Diseases

7.4.2.1 Loose Smut

Loose smut of barley caused by the fungus *Ustilago nuda* (Jens.) Rostr. has a long history of existence. The pathogen is an obligate monocyclic parasite (Neate and McMullen 2005). The disease occurs throughout the world, wherever barley is cultivated (Johnson 2014; Zang 2017). The cool high rainfall area, cloudy weather and moderate temperature (15–22) promote the disease (Sherwood 1997; Johnson 2014). Frequent and high rainfall during flowering period favours the infection and leads to development of loose smut epidemic in a susceptible barley cultivar (Thomas et al. 2017). Loose smut is prevalent in all barley growing states of India; however, its incidence is relatively more in cool and moist areas of northern plains and hills than dry southern peninsular region of the country (Goel et al. 1977). Due to climatic changes and lack of resistance in barley cultivars, the incidence of loose smut has increased in all the major barley growing areas of the country. It is a very destructive disease as almost every ear head of the affected plant is converted into black powdery mass of smut spores and there is no grain formation. The yield loss is, therefore, directly proportion to the per cent smutted ear heads. Barley yield losses of 10–30% due to loose smut are still common in some countries (Zang 2017; Woldemichel 2019).

Symptoms

The systemic infection proceeds soon after germination of infected seed and symptoms are visible only at the time of heading. Infected heads emerge as a mass of dark-brown powdery spores. The entire head gets replaced by dry, olive-brown teliospores masses in sori with little development of floral bracts and awns (Hills 2018). The spore mass is initially covered by a smooth, delicate greyish membrane that soon ruptures and releases the spores (Fig. 7.14a). The spores can easily disseminate by wind and turn the rachis naked (Johason 2014).

In diseased plants, a few or all the spikes are affected but in most of the cases entire spike gets converted into smut sori, though partially infected spikes can often be seen. The fungus infects open flowers and becomes established in the embryo of developing seed. The smutted heads often emerge earlier than healthy heads. These heads normally stand taller in the crop and spores are blown onto adjacent healthy heads by wind. The bare stalk is left and this may be the only sign of the disease late in the season. Infected seeds appear healthy but carry a minute dormant infection inside the embryo (Wallelign et al. 2015; Thomas et al. 2017). Hence, the disease is internally seed-borne. Infected plants appear normal until the emergence of the heads. The disease is most common in cool high rainfall areas and may be more common in the year following a wet spring, which promotes seed infection. In Rajasthan, use of sprinkler irrigation is quite common in major barley growing areas which favour the disease. The pathogen survives from one season to the next only as a dormant mycelium within the embryo of infected barley seeds.

(A)

(B)

Fig. 7.14 (**a**) Covered smut symptoms on barley; (**b**) Covered smut infection in field

Disease Cycle

The infection of loose smut is internally seed-borne. The fungus perpetuates inside the embryo of infected barley seeds as the dormant mycelium, which resumes its activity and invades all part of the plant without causing injury to it (Menzies et al. 2014). The active hypha just behind the growing point keeps pace intercellularly through the young seedlings until it reaches apex of the shoot. The infected heads emerge as a mass of dark-brown powdery spores. Masses of the olive-brown smut spores replace the entire head of plants with little development of floral bracts and awns. The teliospores germinate and invade the female parts of barley flowers and become established in the embryo of developing seed. Once the infected seed matures, the pathogen goes dormant until the cycle is repeated with the germination of barley seed. There is no secondary infection and the disease is monocyclic.

Generally, loose smuts are host specific with their own particular *forma specials* (f. sp.). Loose smut of wheat does not infect barley or oats (Thomas et al. 2017).

7.4.2.2 Covered Smut

Covered smut of barley is caused by *Ustilago hordei* (Pers.) Lagerh. The disease is found in whole of the world and it is more extensively distributed than loose smut of barley (Martens et al. 1984; Mathre 1997). In India, it is common in northern parts where it takes heavy toll of yield in areas where susceptible varieties are grown. In Rajasthan, the incidence of covered smut of barley reported was up to 46% (Mathur and Bhatnagar 1986). Additionally, if carried through the malting process, smut spores can negatively affect the beer quality (Fig. 7.15). Smut means a sooty or charcoal-like powdery mass of teliospores. Smut spores/teliospores are mostly developed in the floral organs.

Symptoms

It becomes visible when the ears emerge. The smutted ears emerge at the same time as those of healthy plants but remain shorter and are usually retained within the sheath for a longer time or may sometimes fail to emerge at all. Every grain in a diseased ear is infected. The typical symptom produced by the disease is the black mass of spores in the infected barley head covered with a persistent membrane (Kashyap et al. 2020). The sori are formed in the ovaries and covered with a silvery semi-persistent membrane until the plants are fully matured (Fig. 7.16a). The entire head of plants are replaced by masses of dark-black powdery smut spores. Sometimes partial development of floral bracts and awns can be seen. The spore masses

Fig. 7.15 Covered smut infected barley seed lot

(A)

(B)

Fig. 7.16 (**a**) Cereal cyst nematode (CCN) infested field; (**b**) Typical symptoms on barley roots with white cysts

are held together due to deposition of a fatty substance and covered with tough membrane.

This feature renders treatment of seeds difficult, unless the fat is removed. The spores are released after the rupture of enclosing membrane during threshing and get attached to the seed surface. CCN remains in dormant state until the seed is sown. Thus, pathogen becomes externally seed-borne in nature. Besides, these infected plants show reduction in height, tillers/plant, tiller length, ears/plant and ear length (Jain et al. 1997). As the barley seed begins to germinate, the teliopores also germinate and invade the seedling along the epicotyl by dikaryotic infection hyphae (n + n). After the pathogen has entered the seedling, its hyphae continue to grow with the shoot and eventually replace the grains by masses of teliospores.

Disease Cycle

The pathogen survives through the externally seed-borne teliospores (smut spores) that have attached on the surface of healthy seeds during threshing or in infested soil. The primary infection is caused by dikaryotic mycelium (n + n) only. When infested seeds are sown, the smut spores germinate on seed coat simultaneously with seeds to produce four meiotic, haploid sporidia. Fusion of two sporidia of opposite mating type results in obligate parasitic and dikaryotic mycelia (Bakkeren and Kronstad 1994). This dikaryon penetrates the host plant through young coleoptiles of the seedling causing primary infection. This leads to systematically infected plants that sporulate exclusively in male or female inflorescence (Laurie et al. 2012). During plant colonization, the dikaryotic mycelium grows in or just below the shoot meristem. The infection proceeds mostly symptomless until differentiation of the colonized meristem into floral tissue, which cues the fungus to proliferate and sporulate in the spikelets of the inflorescence. Mycelium of the pathogen branches rapidly in the crown buds and floral structures. Smut spores are produced by the cells of the hyphae. The hyphae collect in the ovaries and transform into teliospores, which replace the grains. No infection occurs when the primary shoot of the host has grown out above the soil surface. There is no secondary infection and the disease is monocyclic. Soil moisture and soil temperature greatly influence the seedling infection. The optimum temperature for spore germination is 20 °C and the maximum is 35 °C. Deep sowing enhances the period of susceptibility to the infection. A warm, moist, acid soil favours seedling infection.

Management

Seed Certification

Always use certified seeds from authenticated agencies. The permissible maximum limit of smut infection at 0.1% and 0.5% as a certified standard for foundation and certified seeds has been fixed in India by the Central Seed Certification Board (Tunwar and Singh 1988).

Use Resistant Variety

Sharma et al. (2017) reported that barley cultivars PL419, HBL316, Sonu, PL172 and PL 426 were resistant to covered smut under artificial disease inoculation condition.

Heat Therapy

For the eradication of internally seed-borne infection of loose smut, soaking of seed in normal water for 4–6 h followed by dipping in hot water at 49 °C for 2 min and drying before sowing is found effective (Srivastava 2010). Zillinsky (1983) stated that hot water treatment at 50 °C for 10 min can kill the dormant mycelium of loose smut pathogen without harming the seed embryo. The solar heat treatment is effective during bright summer days of May–June. Duhan and Beniwal (2006) proposed soaking of seed in water (1:1 w/v) in a galvanized tub tightly covered with polythene sheet and keeping the seed in bright sunlight. Chaube and Singh (2001) found that solar heat treatment can effectively kill the loose smut pathogen.

Seed Treatment

Seed treatment with systemic fungicides (Carboxin or Thiram or Zineb @ 2.5 g / Kg seeds) is one of the most promising practices for control of seed-borne diseases (Bedi and Singh 1974; Singh 2008). Complete disease control can be achieved by treating the seeds with Mancozeb 50% + Carbendazim 25% @ 0.3% or Tebuconazole 2% DS @ 0.15% or Tebuconazole 60% FS @ 0.1% or Carboxin 37.5% + Thiram 37.5% @ 0.15% (Kaur et al. 2014). Seed treatment with Tebuconazole 2% DS @ 1 g or Carboxin 75%WP @ 2 g or Carboxin +Thiram (1:1) 75%WP @ 2 g/kg seed was found best for controlling the loose smut in barley (Shekhawat et al. 2017).

Bioagents

Seed treatment with *Trichoderma viride* @ 4 g/kg seed with half dose of Carboxin 75% WP @ 1.25 g seed is effective for the control of loose smut (Singh 2004a). Singh and Maheshwari (2001) reported that loose smut can be suppressed completely through seed treatment with any of the bioagents, such as *Trichoderma viride*, *T. harzianum*, *Gliocladium virens* and *Psedomonas fluorescens,* in combination with lower dose of systemic fungicide.

Cultural Practices

The regular inspection of crop at the early heading stage and careful rouging of smutted ears as soon as observed help to prevent spread of the pathogen (Walleling et al. 2015). The smutted ears should be covered with a paper or plastic bag and plucked with scissor.

7.4.3 Cereal Cyst Nematode ("Molya" Disease)

Cereal cyst nematode disease caused by *Heterodera avenae* is widely distributed throughout the world. The CCN is a sedentary endoparasite that infects roots of cereal members of the family Poaceae including wheat, barley, oat, rye and triticale. The CCN was first reported from Germany in 1884 by Khun and has been since reported from several countries including India. In India, *H. avenae* was first reported from a village Neem ka Thana, district Sikar of Rajasthan in 1958 by Vasudeva. The disease caused by the nematode is known as "Molya" (Molya in local language of Sikar and Jaipur denotes "deformed" and disease gets its name due to characteristically deformed root system). The disease now prevails practically in all wheat and barley cultivating regions of the country including Rajasthan (Koshy and Swarup 1971; Mathur et al. 1975; Bishnoi and Bajaj 2004), Punjab (Koshy and Swarup 1971; Chhabra 1973), Haryana (Bhatti et al. 1980; Bajaj and Walia 1985), Delhi (Swarup et al. 1982), Uttar Pradesh (Siddiqui et al. 1986) and Himachal

Pradesh (Koshy and Swarup 1971). However, the incidence of CCN is more in the dry and warmer areas of Rajasthan, Punjab and Haryana and less in cooler climate (Mishra et al. 2005). Singh and Swarup (1964) suggested that level of nematode population in soil is directly correlated with damage to crops and the losses may be 50–100%. The CCN is known as major producing constraint of cereals in India (Singh et al. 2009). Riley and Mckay (2009) reported that yield losses caused by CCN can be up to 90 per cent in severely infested fields. Gaur (2008) noted that molya disease causes losses worth ₹400 million in Rajasthan alone. Ali et al. (2019) reported that CCN is one of the most important cereal pathogens that limit production of small grain cereals like wheat and barley and CCN nematodes alone are estimated to reduce production of crops by 10% globally.

7.4.3.1 Pathotypes

Twelve species of cereal cyst nematode affect root of cereal and grasses (Subbotin et al. 2010), among them three species, namely *H. avenae*, *H. filipjevi* and *H. latipons,* are considered the most economically important (McDonald and Nicol 2005). Rivoal and Cook (1993) stated that *H. avenae* is the most widely distributed and damaging species in temperate wheat producing region of the world. Andersen and Andersen (1982) designated different Indian populations of *H. avenae* to pathotypes Ha 21, Ha 31 and Ha 41. The Jaipur, Udaipur, Narnaul, Sirsa and Delhi, populations of CCN belong to pathotype Ha21 and Ludhiana (Punjab) and Ambala (Haryana) populations belong to pathotype (Ha 41), while Una (Himachal Pradesh) population belong to pathotype Ha31 (Bishnoi and Bajaj 2004; Kanwar 2012).

7.4.3.2 Symptoms

The symptoms caused by members of *H. avenae* group on the roots are differently depending on host. The CCN infested barley fields show usually patchy growth of plants. The number and size of patches depends on degree of infestation. These patches tend to spread with monoculture and may cover the entire field within a span of 3–4 years (Fig. 7.16). Beside patchy growth of stunted plants and general chlorosis, the affected plants are stiffer, thinner with fewer leaves and narrower leaf blades. Tillering is greatly reduced having thin and week grains. If the infestation is uniformly heavy, there is no grain formation. Presence of cysts on the roots is the only confirmatory indication of nematode infestation (Kort 1972). Wheat and barley attacked by *H. avenae* shows increased root production such that the roots have a "bushy-knotted" appearance with several females visible at each knot (Fig. 7.16) (Rivoal and Cook 1993). The *H. avenae* is far common than *H. filipjevi,* both of these species have similar host range and cause similar symptoms and economic losses (Smiley and Nicol 2009). The disease is characterized by the symptoms on roots.

The main root of the diseased plant is elongated with excessive branching of rootlets at the extreme end, giving it a bunchy and knotted appearance due to cyst. These rootlets show slight pear-like swelling at the point of cyst attachment (Fig. 7.16b). Symptoms can be seen within a month after sowing, becoming quite marked by the end of January. During this period, second-stage juveniles are abundant in the soil. Juveniles gain entry to the host root and females set up a feeding site in the vascular system of the root. The female become swollen, produce eggs and are transformed into cysts, which protrude through the roots. The cysts are white when young and then turn brown. As many as 15–20 lemon-shaped cysts can be found on a single plant root. The eggs are formed within the cyst and can survive for long periods of time and over-winter. Eggs hatch out the following season.

7.4.3.3 Disease Cycle

The life of *H. avenae* involves various stages, including the egg, four juvenile stages and adult nematode (Rivoal et al. 1993). *H. avenae* shows sexual dimorphism. Males are vermiform and residents of soil, while females are lemon-shaped bodies turning to brown cysts after death. Under Indian conditions, the white female protruding from the infested roots can be seen clearly. These cysts require a dormancy which extends from April to October (Gill and Swarup 1971). The eggs within a cyst remain viable for several years. During sowing season, the second-stage juvenile emerge from the cyst in late October after the embryo undergoes the first moult within the egg. The optimum temperature for hatching and juvenile emergence is about 20 °C. But the emergence process can take place at a wide range of temperature 10–25 °C. The free living second-stage juvenile hatched out of egg constitutes the infective stage of the nematode and penetrates the host root just behind the growing tip, moving through the cortical cells and stellar region where the larvae remain parallel to the stellar tissues and start feeding on the specialized cells called syncytium surrounding the head (Johnson and Fushtey 1966). The cells involved in syncytial formation include those of endodermis, pericycle, phloem and protoxylem. The movement of the larvae in the cortex results in some damage to cortical cells. The nematode at this stage become sedentary and undergoes three moulting over a period of 4–5 weeks, and then white swollen females protrude from the roots in late December–February. The sexes of the nematode can be distinguished in the third-stage juvenile. Within a short span of time, fourth moult occurs and the fully developed fifth-stage adult male juvenile leaves the roots, wanders in soil and then dies. At the same time, adult female larva formed after the fourth moult grows into typical lemon-shaped structure which retain about 200–500 eggs within the body. Soon after the female dies, its cuticle hardens into tough resistant brown cyst. The cysts help the nematode to survive in the soil to cause infection in the next crop season. The nematode can complete only one generation in a year.

7.4.3.4 Management

Reducing yield loss caused by *H. avenae* requires control of CCN population below the damage threshold.

Resistant Varieties

Use of resistant variety is an effective, eco-friendly and cheapest method of disease control. Barley cultivar RD2035 and RD2052 have been reported to resistant against cereal cyst nematode (Kumar et al. 2017). Koulagi et al. (2018) stated that barley genotypes RD2977, BH959, RD2794 and RD2957 were found resistant to Jaipur and Hisar population and PL874, RD2927 and BH946 were moderately resistant to Ludhiana and Jaipur population of CCN.

Crop Rotation and Fallowing

The population density of *H. avenae* decreased by 70% after continued rotation with mustard, carrot, fenugreek and onion or by fallowing (Handa 1983; Singh et al. 2009). Cultural practices based on rotations of non-cereals, namely carrot, mustard, fenugreek, gram, etc., and clean fallow can effectively control the CCN population (Dababat et al. 2015).

Organic Amendment

It has been known for the past several years that organic manuring influences the development of *Heterodera* species. Mathur (1969) reported that oil cakes, farm yard manure, compost and saw dust applications resulted in improved plant growth and subdued multiplication of the CCN.

Deep Summer Ploughing

Handa et al. (1975) observed decrease in population of cereal cyst nematode with summer ploughings and subsequent increase in the yield of cereals. Soil solarization is very effective to minimize the population density of *H. avenae* (Gill et al. 2017; Mokrini et al. 2017).

Bioagents

A range of microorganisms has been evolved as potential biocontrol agents for CCN including *Pochonia chlamydosporia*, *Trichoderma lilacinum* and *Purpureocillium lilacinus* (Kery et al. 1984; Zhang et al. 2014).

7.5 Future Research Priorities

Despite of tremendous success in host resistance against rusts and a good number of high-yielding rust-resistant barley varieties are available for different agro-climatic areas and production conditions, some other diseases including leaf spot and powdery mildew are becoming bottleneck for the production of barley in the high potential areas of north-western plain zone under changing climatic conditions. Several other issues remain to be resolved in the near future to further strengthen the IDM technologies for successfully minimizing yield losses in an eco-friendly manner. Some important areas that need more attention in future are enlisted as follows:

- Mining of new resistance genes against major plant pathogens including rusts, leaf spots, powdery mildew and CCN.
- Identification and validation of resistance genes by using modern biotechnological tools.

- Development of high-yielding durable and multiple disease-resistant varieties for different traits will be a continuous process as the pathogen keeps evolving correspondingly.
- Management strategies will continue to evolve in response to extended understanding of pathogen distribution and response under changing crop production technologies and environmental situations.
- Identifying candidate genes for QTLs for MAS and genomic selection.
- Evaluation of safe and effective new-generation fungicides against important barley diseases.
- Evolving and validation of indigenous disease management techniques.
- Explore the use of native bioagents for the management of seed- and soil-borne pathogens.

7.6 Conclusion

Like other cereal crops, barley is affected by a number of pathogens that cause considerable reduction in yield and grain quality. In India, though there are many pathogens reported to infect barley, but rusts, spot blotch, net blotch, powdery mildew, leaf stripe, smuts and CCN (molya) diseases are important, causing significant yield losses. Under changing climatic situations coupled with the introduction of high-input barley varieties requiring high fertility and moisture, crops become more vulnerable to pathogens. Though the popular Indian barley varieties are showing resistance against rusts, however, they lack resistance to other diseases especially spot blotch, net blotch and powdery mildew. The leaf spot was considered as a major problem of North-eastern plain zone under warm humid conditions But, at present, it has emerged as a new threat for irrigated barley cultivation in North-Western Plain zone, except the semi-arid region of Rajasthan. The powdery mildew is another limiting factor for barley production in Northern hilly areas. Therefore disease management strategies must focus on the host-pathogen-environment interactions. Moreover, under such circumstances, a single management technique is not enough to provide adequate control of aforementioned diseases. Therfeore, IDM based on the selection and application of a harmonious range of control strategies such as the use of resistant/tolerance varieties, cultural practices, early warning system involving regular pathogen monitoring, bioagents and judicious and timely use of suitable fungicides according to different agro-climatic zones and production conditions is the best tactic to achieve acceptable disease control in barley.

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8 Viral Diseases of Wheat: Research Progress and Future Perspectives

Promil Kapoor

8.1 Introduction

Viruses represent one of the major groups of agronomically important obligate infectious agents/plant pathogens that cause significant yield losses in wheat throughout the world (Table 8.1). At present, more than 40 different viruses have been documented as natural hosts of *Triticum* spp. The most common viruses infecting wheat crop include barley yellow dwarf virus (*BYDV*), wheat mosaic virus (*WMV*), wheat streak mosaic virus (*WSMV*) and wheat spindle streak mosaic virus (*WSSMV*). Generally, these viruses cause several symptoms in the wheat plant including foliar chlorosis appearing as mottles, dashes, blotches or streaks (Bockus et al. 2010; Jones et al. 2010; Zaitlin and Palukaitis 2000). The continuous occurrence of disease outbreaks due to these viruses, together with spatio-temporal dispersal via infected wheat germplasm at local, regional and global scale, also enhances the probability of greater yield losses (Jones 2021). In addition, climate change has also been reported to impact the ecology, biology and epidemiology of wheat viruses and their vectors (Trębicki et al. 2015; Nancarrow et al. 2014). Moreover, under field conditions, the symptoms produced by these viruses are difficult to differentiate from each other, and require skilled personnel and quality laboratory set-up for their accurate identification and diagnosis. As a consequence, several improved serological and molecular techniques from past several years have been developed for their implementation in rapid detection and diagnosis of viruses' load in order to take timely and informed management decisions. Besides immunological tools, other molecular tools [e.g. reverse transcription-polymerase chain reaction (RT-PCR), quantitative RT-PCR (RT-qPCR), rolling circle amplification (RCA) and loop-mediated isothermal amplification (LAMP)] have been developed

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Table 8.1 Major reports of economic yield loss in wheat due to viral infection

Disease	Virus	Yield losses (%)	References
Barley yellow dwarf	*BYDV*	40–50	Larkin et al. (2002)
	BYDV-PAV	84	Nancarrow et al. (2021)
	BYDV	≥50	Riedell et al. (1999)
	BYDV	11–33	Walls et al. (2019)
	BYDV	20–30	Caetano (1982)
Wheat streak mosaic	*WSMV*	30–95	Bockus et al. (2001)
	WSMV	7–13	Hansing et al. (1950); Atkinson and Grant (1967)
	WSMV	18	Christian and Willis (1993)
	WSMV	7	Appel et al. (2014)
	WSMV	83	Lanoiselet et al. (2008)
Wheat spindle streak mosaic	*WSSMV*	3–59	Slykhuis (1970), Gates (1986)
	WSSMV	30	Cunfer et al. (1988), Miller et al. (1992)
Soil-borne wheat mosaic	*SBWMV*	30–70	Rubies-Autonell et al. (2003)
	SBWMV	42.5–52.5	Kucharek and Walker (1974)
	SBWMV	50	Myers et al. (1993)
	SBWMV	80	Prestes and Wietholter (1993)

(Kaur et al. 2020; Kashyap et al. 2016). Furthermore, the new innovations in the whole genome sequencing methodologies enhance the chances of getting ideal markers and barcodes associated with polyphagy, detoxification and virus vectoring abilities in various types of virus biotypes and in turn provide novel opportunities for framing precise and effective strategies safeguarding the wheat crop from their invasion. Moreover, interactions between the viruses and their host plants are dynamic and complex in nature. Several research evidences indicated that a deep understanding of the complex interactome of virus proteins that modify the plant cell machinery and identification of associated host genes will provide excellent opportunities for identifying novel sources of resistance and devising effective virus control tactics (Jarošová et al. 2016). A list of resistance genes deployed for generating resistance against wheat virus has been presented in Table 8.2. The genetic modification of resistance to viruses in wheat through the expression of artificial polycistronic microRNA (miRNA) (Fahim et al. 2012), gene silencing (Yang et al. 2018; Mann et al. 2008; Sanghera et al. 2010) and CRISPR/Cas (clustered regularly interspaced short palindromic repeats/CRISPR-associated) technology (Varanda et al. 2021) will also supplement conventional resistance breeding methodologies to attain a high level of resistance. Since different biotypes of viruses have been reported to cause devastating economic losses in all the wheat-growing regions throughout the globe, an inclusive document providing update information on wheat viruses is warranted. Briefly, the present article emphasizes on the principal viral diseases of wheat of global significance and their management.

Table 8.2 List of resistance genes/QTLs reported to impart resistance against wheat viruses

Disease	Resistance gene/QTLs	Chromosome	References
Barley yellow dwarf	*Bdv1*	7	Veškrna et al. (2009); Zhang et al. (2002), Ayala et al. (2001), Zhang et al. (1999), Banks et al. (1996); Banks et al. (1995)
	Bdv2	7	Jahier et al. (2009), Ayala et al. (2001), Stoutjesdijk et al. (2001); Banks et al. (1995)
	Bdv3	7	Kong et al. (2009), Sharma et al., (1995)
	Bdv4	7	Larkin et al. (1995), Zhang et al. (2001), Lin et al. (2006)
Wheat streak mosaic	*Wsm1*	–	Graybosch et al. (2009)
	Wsm2	–	Lu et al. (2011)
	Wsm3	–	Zhang et al. (2014)
Wheat spindle streak mosaic	*Wss1*	4	Zhang et al. (2005)
	Qym1 (QTL)	2DL	Suzuki et al. (2015)
	Qym2 (QTL)	3BS	Suzuki et al. (2015)
	YmYF	2D	Liu et al. (2005)
	YmIb	2D	Liu et al. (2005)
	YmMD	2D	Liu et al. (2005)

8.2 Major Wheat Viruses and Research Progress

8.2.1 Wheat Yellow Mosaic

Wheat yellow mosaic (WYM) disease is reported as the prime threat for profitable wheat production and is also known as the wheat spindle streak mosaic virus (*WSSMV*). The disease has been reported from several countries including Europe, North America, East Asia, China and Japan (Kühne 2009; Han et al. 2000; Liu et al. 2013; Geng et al. 2019). It was reported for the first time in the 1910s (Kuribayashi 1919) and later reported to have been incited by the wheat yellow mosaic virus (*WYMV*) (Han et al. 2000). The WYM disease is characterized by chlorotic stripes on the leaves, stunted spring growth and reduced tillering (Liu et al. 2005). Diseased crops are compromised with respect to both grain yield and quality (Clover and Henry 1999; Han et al. 2000; Liu et al. 2013; Kühne 2009). Earlier published literature indicated that in the 1990s, the WYM disease affected 666,700 ha area and resulted in the yield loss to the tune of 20–40% (Zhang et al. 2011). Besides this, other workers also reported yield losses to the tune of 70–80% during epidemic situation (Liu et al. 2013).

Wheat yellow mosaic virus (*WYMV*) is a member of Bymovirus (Potyviridae). Structurally, the genome of *WYMV* is encapsidated into filamentous particles and contains two positive-sense single-stranded (ss) RNA segments [RNA1 (7.5 kb) and

(RNA2, 3.6 kb)], where each RNA segment encodes a polyprotein associated with post-translational cleavage (Namba et al. 1998). The polyprotein encoded by RNA1 (269 kDa) synthesized eight proteins including the coat protein (CP) and a nuclear inclusion protein 'b' (NIb) acts as an RNA-dependent RNA polymerase (RdRp) and is responsible for virus replication. In a similar fashion, RNA2 encodes a polyprotein (101 kDa) that produces P1 and P2 proteins of 28 kDa and 73 kDa molecular weight, respectively (Namba et al. 1998). Zhang et al. (2019) revealed that *WYMV NIb* interacts with host (*Triticum aestivum*) light-induced protein (*TaLIP*) to promote the *WYMV* infection by affecting the abscisic acid (ABA) signaling pathway. *WYMV* NIb is not only one of the most conserved portions in the *WYMV* genome, but it is also a good candidate for broad-spectrum resistance (Chen et al. 2014). Indeed, transgenic wheat containing the antisense virus *NIb* has durable field resistance to *WYMV* (Chen et al. 2014).

Several serological and molecular assays for the detection of *WYMV* have been developed including an enzyme-linked immunosorbent assay (ELISA) (Hariri et al. 1996; Geng et al. 2003; Lebas et al. 2009a, b; Takeuchi et al. 2010), immunoblotting (Xing et al. 2000; Han et al. 2000), RT-PCR (Yue et al. 2008; Liu et al. 2013) and loop-mediated isothermal amplification methods (Zhang et al. 2011). Fukuta et al. (2013) developed a novel differential detection method (DD-RT-LAMP) for the simultaneous detection of *WYMV*, Japanese soil-borne wheat mosaic virus (*JSBWMV*) and Chinese wheat mosaic virus (*CWMV*). This method, which involves monitoring the fluorescence during DNA amplification and annealing, makes it possible to detect three viruses simultaneously from wheat or barley leaf samples in one tube within 1 h. Liu et al. (2016) described a robust and sensitive TaqMan-based real-time PCR assay based on the sequence of the *WYMV* coat protein gene for the quantification of in planta virus load. They also elucidated the dynamics of *WYMV* infection and the mechanism(s) underlying resistance in wheat cultivar Madsen.

WYMV is transmitted by an obligate soil-inhabiting fungus (*Polymyxa graminis*) (Inouye 1969) and the thick-walled resting spores and zoospores provide protective covering to the virus (Kanyuka et al. 2003; Kühne 2009). Here, it is important to mention that the dormant spores of *P. graminis* can live for a longer duration in the soil (Chen 2005). As a consequence, it becomes a challenging task to eradicate the inoculum in contaminated fields by using the traditional crop management module or fungicides. There are several control measures for the yellow mosaic disease and they include cultural practices, chemical treatments and introduction of resistant cultivars. However, dormant spores of *P. graminis*, which can carry and transmit the virus, can remain viable in the soil for a long period, and the recommended cultural practices such as crop rotations and late fall plantings of wheat seed do not adequately control the disease. Chemical fumigation of the soil can be effective but it is not a practical option because the fungicide is too expensive for wheat production. Therefore, the effective and advisable strategy to check the progress of viral disease is to cultivate virus-resistant wheat varieties. The development of *WYMV*-resistant cultivars requires an ongoing analysis for resistance genes in wheat. *WYMV* resistance in wheat is manifested by 1–3 genes (Qin et al. 1986), with one dominant gene present on the homologous group 2 chromosome (Zhu et al. 2012; Nishio et al. 2010; Liu et al. 2005). *WYMV*-resistance genes (*YmYF*, *YmIb* and *YmMD*) have been mapped on the long arms of chromosome 2D of the Chinese cultivar Yangfu 9311 (Liu et al. 2005) and the European cultivar Ibis (Nishio et al. 2010). They were also detected on chromosomes 3BS, 5AL and 7BS in the Chinese cultivar Xifeng Wheat (Zhu et al. 2012). The *WYMV* resistance of Madsen (an American highly resistant winter wheat variety) was reported to be controlled by one dominant gene (Takeuchi et al. 2010). By using isogenic lines that carried the dominant Madsen resistance gene in the Hokushin genetic background, Takeuchi et al. (2010) mapped this gene on chromosome 2DL. Suzuki et al. (2015) reported that the *WYMV* resistance of Madsen is governed by two complementary quantitative trait loci (QTLs) (*Qym1* and *Qym2*, located on chromosome arms 2DL and 3BS). They found that the dominance of *Qym1* was incomplete and the homozygous status of the Madsen allele in *Qym1* was necessary for the perfect *WYMV* resistance. With the use of these DNA markers linked to *WYMV*-resistance genes, the development of the new *WYMV*-resistance cultivars should be accelerated. Besides this, some progress has been made in the direction of genetic modification of plants by expressing antisense viral RNA for the production of virus-resistance plants. For instance, transgenic wheat plants carry either complementary DNA (cDNA) of the coat protein of *WSMV* or any RNA interference (RNAi) construct designed by using the nuclear inclusion protein 'a' (*Nla*) gene of *WSMV* to form hairpin RNA results in the production of *WSMV*-resistance wheat.

8.2.2 Wheat Dwarf Disease

Wheat dwarf disease (WDD) is acknowledged as a serious disease in Europe and Asia, where yield losses up to 100% have been observed in winter cereals (Vacke 1961; Najar et al. 2000; Xie et al. 2007). This disease has also been reported from Germany, Hungary, Czech Republic, Asia and Africa (Pribék et al. 2006; Najar et al. 2000; Kapooria and Ndunguru 2004; Bisztray et al. 1989; Commandeur and Huth 1999; Kundu et al. 2009; Liu et al. 2013; Xie et al. 2007; Wu et al. 2008). Besides wheat, WDD has been reported to infect barley, oat, rye, triticale and different species of grasses (Vacke 1961; Liu et al. 2020). Typical symptoms of WDD comprise chlorosis, reddening and leaf streaking and strong dwarfing of the whole plant (Lindblad and Waern 2002; Širlová et al. 2005). WDD is incited by the wheat dwarf virus (*WDV*), which is transmitted by the leafhopper *Psammotettix alienus* in a persistent manner. Ekzayez et al. (2011) also detected the role of *P. provincialis* as a vector in Syria. *WDV* belongs to the genus *Mastrevirus* in the family Geminiviridae. The virions of *WDV* are isometric twinned particles of about 20 × 30 nm (King et al. 2011). The genome of *WDV* comprises of a monopartite, single-stranded (ss), circular DNA (Gutierrez 1999) and is composed of four proteins which are present on the viral-sense strand [capsid protein (CP) and movement protein (MP)] and on the complementary-sense strand [replication-associated proteins (Rep and RepA)] (Gutierrez 1999). Liu et al. (2014) have demonstrated the role of the Rep protein as a

RNA silencing suppressor and established its tight association with the pathogenicity. However, the molecular mechanisms underlying the reason behind the symptom development during *WDV*-wheat interactions are still enigmatic. Recently, Liu et al. (2020) studied the transcriptome of wheat plants infected by *WDV* through messenger RNA (mRNA) expression by RNA-Seq and illustrated the strong linkage between the metabolic and signaling pathway related to phytohormones and photosynthesis in wheat and symptoms' development upon *WDV* infection.

Wheat protection against *WDV* can be achieved by agronomic interventions such as timely skimming, ploughing, shifting in time sowing and chemical control of the virus vectors by insecticides (Širlová et al. 2005). Vacke and Čibulka (2000) reported that moderately susceptible varieties could play an effective role in providing protection against *WDV*, especially in the regions of high and periodic virus occurrence.

8.2.3 Wheat Streak Mosaic

Wheat streak mosaic (WSM) caused by the wheat streak mosaic virus (*WSMV*) (McKinney 1937; Staples and Allington 1956) is an important global disease of wheat. *WSMV* is reported from several wheat-growing regions of the world and include countries like Argentina, Australia, Brazil, Canada, Europe, Iran, Mexico, New Zealand, Turkey and USA (Navia et al. 2013; Hadi et al. 2011). Wheat losses due to *WSMV* ranged from 7 to 13% in Kansas (Atkinson and Grant 1967), 83% in Australia (Lanoiselet et al. 2008) and 18% in Canada (Christian and Willis 1993). *WSMV* is the type member of the genus *Tritimovirus* in the family Potyviridae and can be identified by the filamentous, flexible, non-enveloped, rod-shaped structure (Rabenstein et al. 2002). The genome size of *WSMV* lies between 9.3 and 9.4 kb and is composed of a monopartite, positive-sense, single-stranded RNA genome (ssRNA +). The *WSMV* genome contains a single open reading frame (ORF) and transcribed into a large polyprotein, which later cleaves into 10 mature proteins. These cleaved proteins are: coat protein (37 kDa), nuclear inclusion putative polymerase (57 kDa), helper component protease (44 kDa), viral protein genome-linked proteinase (23 kDa), nuclear inclusion putative protease (26 kDa), 6 kDa protein, cytoplasmic inclusion protein (73 kDa), and P1 protein (40 kDa), P3 protein (32 kDa) (Singh et al. 2018; Chung et al. 2008; Choi et al. 2002; Stenger et al. 1998). Wheat curl mite (WCM) (*Aceria tosichella* Keifer) is responsible for the transmission of *WSMV*, which is hosted by the species of the Poaceae family such as barley, maize, oat, wheat, millet, *Setaria* and *Echinochloa* spp., and grasses (*Digitaria sanguinalis*, *Avena fatua*, *Avena strigosa*, *Panicum miliaceum*, *Lagurus ovatus*, *Lolium multiflorum*, etc.) (Dráb et al. 2014; Seifers et al. 2009; Chalupníková et al. 2017; French and Stenger 2002).

The initial symptoms of WSM disease appear on young foliage as light green streaks which later extends to form irregular yellow to pale green stripes, resulting in a mosaic pattern along the leaf veins (Vacke et al. 1986). Wheat infected prior to significant tillering is severely impacted and becomes stunted, yellowed and rosetted

(Hunger et al. 1992, Byamukama et al. 2012). *WSMV* infections reduce root biomass and water use efficiency (Price et al. 2010; Langham et al. 2001a, b). Heavily infected plants either produce no spikes or if produced, they are partially filled with shrivelled kernels (Atkinson and Grant 1967). Recent research investigations made by Tatineni et al. (2017) suggested that the formation of severe chlorotic streaks and spots, followed by acute chlorosis in wheat, is due to the deletion of coat protein (CP) amino acids 58–84. However, visual symptoms appeared on the foliage are not a positive confirmatory test for *WSMV* because of symptom expression similarity with other viruses. Serological methods such as enzyme-linked immunosorbent assay (ELISA) and its variants [double antibody sandwich (DAS)-ELISA and triple antibody sandwich (TAS)-ELISA] are well-acknowledged procedures for the monitoring of viruses. Unfortunately, they are less effective and sensitive in comparison to cDNA amplification-based PCR assays. Other demerits of serological assays in comparison to PCR-based assays include low sensitivity (Sharma et al. 2017; Izzo et al. 2012), inefficiency to detect low viral load (Schubert et al. 2015) and inability to read all closely related viral strains (Coutts et al. 2008). Later, molecular procedures based on RT-PCR or its variant RT-qPCR have been reported by several workers to detect *WSMV* in plants (Schubert et al. 2015; Dráb et al. 2014; Gadiou et al. 2009) by employing the viral coat protein (CP) as the target site (Singh and Kundu 2017; Gadiou et al. 2009). Lee et al. (2015) developed a *WSMV*-specific LAMP assay and found it to be useful in the quarantine inspections of imported wheat, oats, corn and millet.

The protection of wheat from *WSMV* infection is primarily oriented towards the reduction or elimination of the risks of infection, owing to the fact that *WSMV* and its mite vector are difficult to control by the chemicals (Fritts et al. 1999). Therefore, the most promising approach for the control of *WSMV* is cultural and agronomic operation that helps in minimizing the sources of mites and virus. Besides this, post-harvest weed control and planting date are also crucial. Pre-harvest volunteer wheat and grassy weeds, which served as a reservoir for the *WSMV*, can be efficiently controlled with the help of herbicides or tillage operations. Therefore, for an effective management, it is advisable to completely eradicate the volunteer wheat at least 2 weeks prior to sowing. Early wheat sowing should be discouraged, as substantial yield losses due to heavy and widespread infections of the virus and mite occurred in early sown wheat (Slykhuis et al. 1957; Hunger et al. 1992). Wheat sowing should not be done next to late-maturing summer crops (e.g. foxtail millet, maize, sorghum or small grain cover crops), as they are the preferred hosts to wheat curl mite (WCM) or *WSMV*.

Host resistance is the best way to reduce the yield loss caused by *WSMV* or WCM (Chalupniková et al. 2017; Richardson et al. 2014; Thomas et al. 2004; Singh et al. 2018). Wheat varieties showing resistance to WCM have been developed by Harvey et al. (1999); however, they later on suffered from mite-resistant strains and compromised their effectiveness against *WSMV*. 'Mace' cultivar developed by Graybosch et al. (2009) was the first commercial variety to be released with strong resistance to *WSMV* conferred by the *Wsm1* gene, but it soon became ineffective against *WMV* (Tatineni et al. 2010; Byamukama et al. 2012). So far, three resistance genes (*Wsm1*, *Wsm2* and *Wsm3*) imparting tolerance towards *WSMV* and its vector (WCM) have been documented and incorporated into wheat (Fahim et al. 2012; Seifers et al. 2013). However, *Wsm2* gene is the extensively explored and successfully incorporated gene in a number of wheat cultivars, such as Snowmass (Haley et al. 2011), RonL (Seifers et al. 2006), Oakley CL (Zhang et al. 2015) and Clara CL (Martin et al. 2014). An integrated pest management (IPM) module that amalgamates various aforementioned approaches and strategies must be followed strictly to diminish the losses caused by *WSMV*. Based on this concept, an integrated disease management outline has been portrayed by McMechan and Hein (2016) and highlighted that host resistance and delayed sowing were effective in increasing the winter wheat yield, even under high disease pressure of *WSMV*.

8.2.4 Yellow Dwarf Disease

Yellow dwarf disease (YDD) is a serious problem of wheat and the current climate change provides a congenial environment that makes YDD one of the prime concerns for quality wheat production (Saulescu et al. 2011; Jones 2021). YDD is caused by two different viruses viz., barley yellow dwarf virus (*BYDV*) and cereal yellow dwarf virus (*CYDV*) of the Luteoviridae family. Their infections occur singly or as mixed infection. Both viruses cause the same types of YDD symptoms in infected wheat plants, and both are persistently aphid transmitted and have the potential to decline wheat yield by 11–33% (Walls et al. 2019). Their most important aphid vectors are *Rhopalosiphum padi*, *R. maidis*, *Sitobion avenae* and *Schizaphis graminium*. *CYDV* is transmitted by *R. padi*, whereas the main vectors of *BYDV* strains PAV, MAV, RMV and SGV are *R. padi* (PAV), *R. maidis* (RMV), *Sitobion avenae* (MAV) and S*chizaphis graminiu*m (SGV) which feed upon, and transmit the viruses to wheat, oats, rye, corn and barley, in addition to 150 other grass hosts of the Poaceae family (Miller and Rasochová 1997). As a consequence of broad host range and complex life cycle of the *BYDV* vector, the management of yellow dwarf disease becomes a perplexing task and therefore demands location- and climate-specific disease management tactics. *BYDV* is transmitted by aphids in a circulative-persistent manner (Walls et al. 2019; Miller and Rasochová 1997) and plants infested with *BYDV*s show stunted growth, chlorosis and discolouration. Under severe infestation of *BYDV*s, 66% wheat yield loss due to the cumulative effect of the reduction in seedling size, heading and chlorosis has been reported by Oswald and Houston (1953). It is important to mention here that susceptible species of the Poaceae family can be infected by the virus at any time throughout their life cycle; however, winter wheat is highly susceptible to the virus infection, either during seedling stage (Zadoks growth Stage 31) or just during the beginning of stem elongation stage (Oswald and Houston 1953; Smith and Sward 1982).

Generally, wheat tolerance towards *BYDVs* is not a natural event. Earlier published literature indicated that the resistance gene is present in the wild relatives of wheat (e.g. *Thinopyrum* spp.) (Zhang et al. 2009) and its incorporation into the commercial cultivar is not reported yet. It has been observed that the tolerance of wheat (cv. Anza) towards *BYDV* is conferred by a major dominant gene (*Bdv1*) present on the short arm of chromosome 7D, of Brazilian spring wheat (cv. Frontana) (Singh et al. 1993; Ginkel and Van Henry 2002). Further, Zhang et al. (2009) revealed that the *Bdv1* gene imparts tolerance only towards *BYDV-MAV* under field conditions and is unable to express resistance against all the *BYDV* strains or in all the environments (Zhang et al. 2009), reflecting the polygenic and complex nature of resistance (Ayala et al. 2001). A large-scale resistance screening of wheat and wild germplasm against *BYDV* resulted in the identification of *bdv2* as a resistance gene in *Thinopyrum* spp. (Zhang et al. 2009; Ayala-Navarrete et al. 2013; Sharma et al. 1995; Francki et al. 2001), which was later reported to impart broad-spectrum resistance to *BYDV* (Dewar and Foster 2017) and successfully introgressed from *T. intermedium* onto wheat (Ayala et al. 2001; Zhang et al. 1999). Functionally, it was observed that the *bdv2* gene present in the resistant host helps in the activation of pathogen-associated molecular pattern-triggered immunity (PTI) and regulates the synthesis of pathogenesis-related genes to lessen the virus titre (Wang et al. 2013). Besides this, a series of Triticeae species of the genera *Agropyron*, *Thinopyrum*, *Elymus*, *Pascopyrum*, *Elytrigia* and *Leymus* have been documented as resistant accession to *BYDV* infection (Barloy et al. 2003; Xu et al. 1994; Makkouk et al. 1994; Larkin et al. 1990; Sharma et al. 1999). Additionally, a few octoploid wheat/*Thinopyrum* partial amphiploids developed either from wheat × *Th. Intermedium* or from wheat × *Th. ponticum*, wheat alien addition, substitution and translocation lines have been identified as potential candidates for *BYDV* resistance (Barloy et al. 2003). CPI 113500, an amphidiploid derived from *Agropyron pulcherrimum*, also shows a strong resistance level against *BYDV* (Xin et al. 2002; Jarošová et al. 2016).

Gene pyramiding is an ideal approach for the incorporation of multiple resistance genes from different backgrounds into a single genotype. This approach has been illustrated by Chain et al. (2006) to reduce the viral replication of *BYDV* and minimize likely impacts of more harmful viral strains by incorporating *BYDV*-resistance genes (e.g. *Bdv1* gene) from another partial resistance source. Later, it was observed that the incorporation of two or more resistance genes into one genotype imparted strong resistance than single gene (Riedel et al. 2011; Jahier et al. 2009). It is important to mention here that the incorporation of both partial resistance genes (*Bdv2* and *Bdv4*) into wheat results in poor growth of the virus inside the plant because both the genes have distinct modes of action (Barloy et al. 2003; Chain et al. 2005) and therefore gene pyramiding is widely acknowledged as an ideal approach for attaining a strong level of resistance against *BYDV-PAV* than individual source (Jahier et al. 2009). However, synergistic effects of both *Bdv2* and *Bdv3* are still debatable (Anderson et al. 1998). Therefore, breeding of wheat lines with multiple resistance genes (e.g. *Bdv2* and *Bdv4*) seems to be an ideal and promising strategy for imparting virus resistance in plants.

From last three decades, several attempts have been made by various researchers for generating transgenic wheat that impart resistance towards *BYDV-PAV* strains (Jarošová et al. 2016). Dupré et al. (2002) transformed three wheat genotypes with gene constructs composed of open reading frames (ORFs) encoding coat protein

(CP), replicase (Pol), movement protein (MP) or non-coding sequence (NCS), corresponding to the promoter of subgenomic RNA2. They obtained highly variable results and were unable to achieve absolute resistance against *BYDV-PAV*. Similarly, Cheng et al. (2002) made an attempt to generate transformed wheat by incorporating a gene construct containing *BYDV-GPV* coat protein gene by following gene bombardment and the pollen tube pathway-based transformation methodologies. Pollen tube pathway-based transformation strategy resulted in the development of *BYDV*-resistant plants in comparison to gene bombardment approach where transformed plants showed susceptibility towards *BYDV* strains. Later, Yan et al. (2006) utilized *pac1* gene for the genetic transformation of wheat for imparting resistance against *BYDV*. Functionally, Pac1 encodes a double-stranded RNA-specific RNase III enzymes and is responsible for the degradation of double-stranded viral RNA formation during *BYDV* replication process inside the plant. It is important to highlight that Yan et al. (2006) achieved success in obtaining strong resistance in transformed plants, but the level of resistance is greatly influenced by the dosage of the inoculum.

BYD disease can be controlled effectively by selecting virus-resistant or -tolerant cultivars, appropriate sowing date, effective insecticidal seed treatments and timely application of insecticide sprays. The most important step in managing aphid vectors of *BYDV*s is the optimized planting date. It has been reported that the late planting is useful for reducing *BYDV* infections in the field (Coceano et al. 2009; Kelley 2001). Ideally, wheat sowing after Hessian fly-free dates is advantageous for preventing aphid migration (Isleib 2015). Insecticide-treated seeds can be utilized to counterbalance the susceptibility of early sown wheat to aphids. In this case, Imidacloprid, a neonicotinoid, seed treatments can be a good option to protect wheat crop from primary infection of the virus, that is, usually 3–5 weeks post-seed emergence (Gourmet et al. 1996; Royer et al. 2005). However, insecticide success depends on the method and chemical applied for seed coating. Several times repeated application of insecticide is advantageous later in the season for the effective and timely management of BYD (Kennedy and Connery 2012). Unfortunately, there are several drawbacks associated with the usage of pesticide-treated seeds. For instance, they are expensive than untreated seeds. Besides this, they can pose insecticide residue problems in the soil, disrupt aquatic and natural soil ecosystems, and cause non-target effects on pollinators and other useful microflora (Goulson 2013; Krupke et al. 2012). After sowing, foliar spray of insecticide(s) is the best and valid management strategy to prevent aphid vectors, owing to the fact that aphids require time to acquire and inoculate *BYDV*s. Although, in the case of aphid transmitted *BYDV*, chemical insecticides or repellents have been used to maintain the aphid population below economic threshold level (i.e.15 aphids per one-foot row of plants) during early post-emergence stage (Herbert et al. 1999). Pyrethroid and Pirimicarb insecticides can be utilized as foliar sprays for the effective management of aphid population under field conditions (McKirdy and Jones 1996).

8.3 Conclusion and Future Outlook

Wheat viruses and their vectors have been reported to be the cause of huge yield and monetary losses around the world and due to climate change, there will be a shift in the importance of these pathogens in coming time. There will be a greater chance that in the northern wheat-growing areas, insect-transmitted viruses will become more important. Consequently, there is a continual need to adapt wheat production systems to the changing importance of viral diseases and their insect vectors thereby, to develop new effective agrochemicals. Resistant or tolerant genotypes are considered as one of the most ideal, eco-compatible and safest methods for the effective management of viral diseases in wheat. Traditional wheat breeding programmes along with transgenic and genomic methodologies have been undertaken, and substantial efforts have been extended at the global level for searching and identifying germplasm sources resistant to viruses and their vectors. Additionally, to enhance the present understanding of viruses and their vector resistance, novel resistance genes should be isolated and characterized for their effective deployment as genomic resources. Besides this, genetic characterization of insect avirulence factors will be helpful in the prediction and assessment of the potential resilience of specific host resistance gene(s). In conventional breeding, sources of resistance have been utilized from the primary gene pool at large scale and only few from secondary and tertiary gene pools have been drawn. However, there are several other wheat-related species, in which gene(s) imparting resistance to the virus or their insect vector can be present. Therefore, conventional breeding methods deploying new sources of resistance might be a promising tactic and in the present scenario of rapid climate shift, they should be one of the top priorities. More importantly, to reduce yield losses caused by viral diseases, an efficient collaboration between phytopathologists, breeders, geneticists and specialists on wheat production system is desirable. As all the wheat production starts with seed, breeding for resistance is of prime importance in this context. Improving resistance in the first step requires identification of genetic resources in wheat and its wild relatives, followed by the analyses of genetics of resistance and the development of molecular markers. The availability of genomic tools such as CRISPR/Cas9 (clustered regularly interspaced short palindromic repeats/CRISPR-associated 9) in wheat will speed up the isolation and characterization of resistance genes which, in turn, will facilitate the detection of new and, perhaps more efficient, alleles. In the future, breeding for resistance may take place at an allele level and therefore the process may become more effective. New technology, such as next-generation RNA sequencing of wheat infested with galaxy of viruses, will offer quality information into host factors that differentially interact with the virus, thus increasing the understanding on different modes of wheat-virus interactions, as well as the nature and routes of long-distance movement of viruses in their plant hosts. Cultivars with a high level of resistance to the most prevalent pathogens in their growing area will ensure yield and facilitate the development of sustainable wheat production systems by allowing soil conserving production systems with minimal input of pesticides, thereby minimizing the harmful impact of viral disease pandemics and epidemics upon food security and human health in a socially and environmentally accountable manner.

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Part II

Innovations in Entomology and Nematology Research

9 Biology and Management Strategies of Major Insect-Pests of Wheat

Poonam Jasrotia, Beant Singh, and Mohini Nagpal

9.1 Introduction

Wheat (*Triticum aestivum* L.) is a prime cereal occupying about 219.6 million hectares with annual global wheat production of 731 million tonnes feeding approximately 2.5 billon world population (FAO 2021). The top wheat-growing nations are China, India, the USA, Russia, France, Canada, Germany, Turkey, Australia and Ukraine. Annually, the wheat yields are increasing at 0.9% per year, which is less than 2.4% as desired to double global production by 2050. With the current growth rate, wheat yield will increase only 38% by the end of 2050 (Ray et al. 2013). One of the important reasons for not achieving the desired growth rate is the problem of biotic and abiotic stresses in wheat crop which is on surge and various management strategies are being used to manage them. Insect-pests and diseases mainly constitute biotic factors that are directly affecting yield and quality of the crop. As per an estimate by Pimentel et al. (1997), globally across the World approximately about 20–37% of yield is lost due to pest attack leading to monetary loss of $70 billion annually. Depending on the availability of host and insect feeding behaviour, herbivore insects have the ability to attack a host and move from one crop field to another crop field in agro-ecosystems. In one crop season, one particular insect pest can attack multiple crops that make pest management options more difficult and in such scenario, crop rotation as IPM tool does not work. Besides this, pesticide resistance is increasing day by day which indicates the reduced susceptibility of insect-pests to the pesticide. All this is result of indiscriminate usage of conventional pesticides.

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Wheat crop plays a significant role in world economy by serving as a staple food for a vast majority of people. Earlier, the crop was considered as an insect-pest free crop but after the onset of green revolution and modifications in production and protection technologies, a number of insect-pests were reported to attack wheat crop. However, some regional pests observed in wheat-growing areas which are of minor importance are also sometimes becoming major damaging pests of the crop. Insect-pests encountered in wheat-producing areas attacking wheat mostly belong to sucking and lepidopterous insect categories. The common insect-pests of the wheat crop are termites, aphids, pink stem borer (PSB), armyworm, brown wheat mite, wheat stem sawfly, cereal leaf beetle, pod borer, Ghujia weevil, wheat midge and Hessian fly (Table 9.1).

Various management options viz., mechanical, cultural, physical, biological and chemical are available for wheat insect-pest management in the field (Katare et al. 2017). However, under higher pest-pressure only insecticides can give sufficient protection, but these are expensive, environmentally undesirable and have a problem of development of insecticide resistance. Therefore, incorporation of genetic resistance in wheat varieties may be an alternative in the case of aphids, as it is sustainable, cost-effective and environmentally safe. In addition, in the present scenario it is important to understand the mechanism of aphid resistance operating in wheat genotypes through molecular approaches, so that the various resistance pathways responsible can be identified. Besides, the testing of new biopesticides as an environmentally compatible alternative to conventional insecticides for pest management and their incorporation in IPM is pertinent, considering ill effects of chemical insecticides (Katare et al. 2018). New pest management strategies involving cross-sectoral approaches which are climate friendly should be developed to reduce crop losses induced by pests, increase ecosystem services and resilience of agricultural systems in the face of climate change. Development of climate-smart pest management practices and their implementation along with other climate resilient crop production technologies will help to manage the changing pest threats more effectively and will also lead to more efficient and robust food production systems (Heeb et al. 2019). This chapter will discuss important key pests of wheat crop and their biology and management practices.

9.2 Major Insect-Pests of Wheat

Wheat crop is attacked by about half a dozen insect-pests from seedling to maturity stage. The list of important insect-pests infesting wheat crop is given in Table 9.1.

9.2.1 Termites *Odontotermes Obesus* (Ramb), *Microtermes Obesi* (Holm)

Termites or white ants are designated as severe destructors of wheat crop that can attack any crop growth stage (Sharma et al. 2004; Rouland-Lefèvre 2010; Paul et al.

Table 9.1 Major insect-pests attacking wheat, their damaging crop stage and distribution

Name of the insect-pest	Scientific name	Damaging crop stage	Distribution	References
Termites	*Odontotermes obesus* (Ramb) and *Microtermes obesi* (Holm)	Seedling to ripening	Africa and Asia	Rouland-Lefèvre (2010), Paul et al. (2018), Chellappan and Ranjith (2021)
Aphids	Foliar aphids: *Rhopalosiphum maidis*, *R. padi*, *Sitobion avenae, S. miscanthi, Schizaphis graminum*, *Diuraphis noxia, Metopolophium dirhodum*	Seedling to earhead	Africa, Asia, Europe, North America, Oceania and South America	Zhang et al. (2012), Yazdani et al. (2018), Botha (2020)
	Root aphid: *Rhopalosiphum rufiabdominalis*	Seedling and tillering	Africa, Asia, Europe, Oceania, North America and South America	Cope et al. (2016)
Pink stem borer	*Sesamia inferens*	Booting to dough	Asia, North America and Oceania	Beant (2012)
Armyworm	*Mythimna separata* (Walker)	Seedling and tillering	Asia, Europe and Oceania	Duan et al. (2017), Hou et al. (2018), Chen et al. (2019)
Brown wheat mite	*Petrobia latens* (Muller)	Tillering to ripening	Africa, Asia, Europe, North America and Oceania	Fenton (1951), Sitz et al. (2019)
Wheat stem sawfly	*Cephus cinctus* (Norton)	Seedling and tillering	Asia and North America	Shanower and Hoelmer (2004), Fulbright et al. (2017)
Cereal leaf beetle	*Oulema melanopus*	Seedling	Africa, Asia, Europe and North America	Dosdall et al. (2011), Philips et al. (2011)
Pod borer	*Helicoverpa armigera*	Ear emergence to ripening	Africa, Asia, Europe, North America, Oceania and South America	Tay et al. (2013), Czepak et al. (2013)
Ghujia weevil	*Tanymecus indicus* Faust			Gaur and Mogalapu (2018)

(continued)

Table 9.1 (continued)

Name of the insect-pest	Scientific name	Damaging crop stage	Distribution	References
		Flowering and grain filling	India, Myanmar and Ceylon	
Wheat midge	*Sitodiplosis mosellana* (Géhin)	Dough stage	Africa, Asia, Europe and North America	Chavalle et al. (2015), Echegaray et al. (2018), Olfert et al. (2020)
Hessian fly	*Mayetiola destructor* (Say)	Tillering to ripening	Africa, Asia, Europe, North America and Oceania	Schmid et al. (2018), Liu et al. (2020)

2018). Amongst 12 families, about 75% of all termites belong to one largest family, Termitidae (Chellappan and Ranjith 2021). Globally, *Odontotermes obesus* (Ramb) and *Microtermes obesi* (Holm) are considered as the most noxious species of termites attacking wheat crop (Chhillar et al. 2006). Generally, termite attack in wheat is more serious at 3–4 weeks after germination and at the earhead stage. The termites feed on roots and underground portion of the stem causing the affected plant to wilt and wither. Complete drying of damaged plants occurs after the attack and the damaged plants can be easily pulled out. At the earhead stage, the damaged plants produce "white ears" and these plants cannot produce any grains. Heavy infestation of termites is noticed in fields where raw farmyard manure is used before sowing and is found to be under unirrigated as compared to irrigated conditions. Termites are also capable of degrading wheat straw lignin and polysaccharides through the presence of gut bacteria viz., *Bacillus* sp., *Enterobacter* sp. and *Ocrobacterium* sp. These gut bacteria help in biodegradation of wheat straw and other similar lignin containing biological wastes (Borji et al. 2003).

9.2.1.1 Biology

Termites belong to the category of social insects and are found in colonies known as termitaria. The size of the colony varies from few hundreds to millions of individuals. The colony consists of three castes viz., workers, soldiers and reproductive. The reproductive are sexual forms and comprise the "queen" and "king" that are associated with dispersal, pair bonding and fecundity. Workers help in nest construction, foraging, tending and feeding of immature and queen. The sterile wingless females constitute the soldier caste and assist in protecting the colony from invaders, for example, ants. Cellulose is the main component that termites get by feeding on dead plant fibre. Many termites support a fungus within the nest, which is a source of proteins for the queen, king and the young larvae. The new colony of termites is formed when the swarms of sexual form leave their nests and fly to various places. The shedding of wings takes place and a nest is created. Annually, the queen can lay up to thousands of eggs singly in a nuptial chamber after a brief courtship between the male and a female (future king and queen). In a colony, seven nymphal instars are normally there and the period for incubation varies from 24 to 90 days. However, based on the size and age of the colony, temperature and prevailing environmental conditions, this number may vary. The nymphs can develop into either soldiers or workers. The total life span of workers is 1 or 2 years. A mature colony can have 200,000–2,000,000 workers depending on the species of termite, although many colonies may have as few as 50,000–60,000. In a colony, 80–90% of the members are workers and about 10% are soldiers. After leaving the colony a few years later, sexual forms of termites make new colonies (Srivastava 1993).

9.2.1.2 Management Strategies

Presently, insecticides are the mainstay for termite management strategies in wheat crop worldwide (Peterson et al. 2006; Potter 2011). Temporary cultural control tactics such as crop rotation, deep tillage practice, residue removal, early harvesting and application of fertilizers for healthy plant stands are also advocated for their management (Rouland-Lefèvre 2010). High-density sowing of wheat is also suggested for termite management. Appropriate number/stand can be achieved by thinning on plants that survive termite damage. For termite management, Pusa-push-pull practice in wheat is also recommended (Mahapatro et al. 2017).

Amongst the various methods to manage termites, seed treatment is found to be quite effective against termites. The application as seed treatment with Chlorpyriphos 20 EC @ 4.5 ml/kg provides an effective control of termites. Besides, the seed treatment with Fipronil (Regent 5FS @ 0.3 g a.i./kg seed) or Imidacloprid 17.8% SL @ 0.6 g a.i./kg seed is also reported to provide a better control of termites (Kumar et al. 2020). The broadcasting of the insecticide-treated soil at the time of first irrigation can also be practiced in the standing crop for termite control. The treatment of Chloropyriphos 20 EC @ 3 L mixed in 50 kg soil can be broadcasted for 1 ha field. The application of Chlorpyriphos 0.8 L with 50 kg soil and broadcast in 1 ha field followed by light irrigation can also be used if seed treatment is not used. Effective termite management with soil application of Chloropyriphos 20 EC @ 1.25 kg a.i./ha or quinalphos 1.5% dust had been reported by Kishore and Sharma (2007). Mishra et al. (2007) reported that the application of Imidacloprid @ 2.0 ml/kg, followed by Chloropyriphos @ 5 mL/kg, outturns/concludes the maximum plant stand (77.7 plants/m^2), minimum damaged tillers (5 tillers/plot) and maximum grain yield (42.2 q/ha). Lower dosage, that is, Fipronil 0.3% GR @ 20 kg/ha can be used for the effective management of termites in wheat and it does not produce any phytotoxic effect on wheat (Kambrekar et al. 2016).

As a biological control option, the application of entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* had also been reported to be effective against adult termites. Application of the fungal formulations can be used as seed treatment and can be applied to the planting holes or bases of stem at planting time. Besides, single soil application of entomopathogenic nematode-based Pusa Nemagel at the time of sowing is reported to decrease the termite incidence by 48–78% and can lead to wheat yield increase from 22.2% to 43.3% (Rathour et al. 2014). Because of the behavioural responses of termites to infected individuals and their social structure besides loss to predators, significant effective results for termite control have not been obtained with the use of predators or pathogens.

9.2.2 Aphids

Amongst the different insect-pest damaging wheat crops, a number of aphid species are known to attack wheat crop. The major aphid species that cause infestation to wheat include *Rhopalosiphum maidis*, *R. padi*, *Schizaphis graminum*, *Diuraphis noxia*, *Metopolophium dirhodum*, *Sitobion avenae*, and *Sitobion miscanthi* (Hughes and Maywald 1990; Zhang et al. 2012; Yazdani et al. 2018; Botha 2020). Besides, one aphid species *Rhopalosiphum rufiabdominalis* attacks roots of the wheat plant. Furthermore, threats due to non-indigenous species of aphids in other countries have been reported to increase because of globalization and connectedness via world trade (Cope et al. 2016). Both adults and nymphs cause damage by sucking cell sap, thereby reducing the vitality of the plants. The leaves of infested plants give a pale and silky appearance and the plants finally wilt. In addition, aphids also release honeydew due to which black sooty mould develops on leaves that reduces the photosynthetic activity of plants. The main feeding areas of aphid on wheat plant are flag leaf sheath, main stem and developing kernels at the flowering stage, resulting in the death of spikes, shrivelled and empty grains. Aphids inject saliva on the leaves resulting in yellow or whitish streaks (Kazemi et al. 2001). Under heavy infestation, symptoms like stunted growth, reduced leaf area, bleached spikes, purplish streaks on tiller, dry weight loss and low chlorophyll content appear (Millar et al. 1994; Burd and Elliott 1996) due to disruption in electron transport chain in leaves fed by aphids (Haile et al. 1999). Infestation occurs usually during January, till crop maturity. Numerous biotypes based on genetic differences of aphids have been recorded in cereal-producing countries globally (Weng et al. 2007). In addition, aphids are responsible for indirect yield losses in cereals by transmitting an important viral disease such as barley yellow dwarf (BYD). Sap sucking by aphids leads to simultaneous transmission of BYD and produces severe damage to crop (Riedell et al. 1999). Loss associated with sucking plant sap includes yield drop by 15% and that with BYD transmission could be as high as 70%, which concludes an average loss of 22% provided severity of infestation. As per an estimate made during 1987–1993, the economic impact due to wheat aphids in Western United States was reported to be to the tune of $893 million (Morrison and Peairs 1998) and in Canada around 37% yield losses were reported in winter wheat (Butts et al. 1997).

Avila et al. (2019) generated an aphid distribution model map and listed regions with aphid attack as temperate and Mediterranean areas in Australia and Europe and semi-arid areas in north-western China and Middle Eastern countries. New climatically vulnerable regions for the establishment of aphids were included in the updated version of the model, which was not previously reported. These included regions were parts of New Zealand, France, and the UK. The origin of the English grain aphid (*S. miscanthi*) is Asiatic and is widely distributed in India, China and the Far East and in the Pacific region (Blackman and Eastop 2007). However, the corn leaf aphid (*R. maidis*) is found globally throughout the tropics, subtropics and warmer temperate regions.

9.2.2.1 Biology

The aphids are soft-bodied, lime-green coloured insect with a darker green stripe on its back. The aphids are holocyclic species and exist in different stages, viz., winged (alates), wingless (apterous), sexual and asexual forms. The rapid spread takes place through asexual reproduction where viviparous females give rise directly to nymphs rather than eggs. While alates disperse the population and infection to the host, apterous is mainly responsible for physical damage to the plant such as curling and sucking the immature leaves. Parthenogenetic multiplication occurs in the case of bird cherry-oat aphid (*R. padi*) for one or more than one generation and afterwards it undergoes sexual reproduction. During the course of autumn, alates fly to the primary host to mate and produce eggs, whereas the feeding symptoms of these aphids are almost absent. There are four nymphal instars and the period of each instar is around 2–3 days. The whole development cycle is completed in 7–8 days depending upon temperature conditions. The aphids complete more than 10–15 generations per season. The developmental rate, number of progeny and adult longevity are mainly affected by the host species and its age, and temperature. Fast reproduction can occur under favourable conditions, leading to population outbreaks. Temperature and plant growth stage form an integral part of aphid population development with minimum threshold temperature for immature development (−1.57 °C) and maximum intrinsic rate during jointing stages of wheat (18–21 °C). However, extreme warmth can possibly limit the survival and dissemination of the aphids.

9.2.2.2 Management Strategies

Various control measures viz., cultural, physical, mechanical, biological, chemical and host plant resistance can be utilized to check the aphid population below the economic threshold level. However, under favourable weather conditions, the aphids can be extremely injurious and can occur in large numbers and can then only be managed by chemicals. However, enormous amounts of pesticides are being used on different crops and these are costly and destroy non-targeted beneficial natural enemies (Jasrotia and Katare 2018). This also leads to high levels of pest resistance and resurgence.

Amongst cultural control strategies, changes in sowing times can be helpful for managing aphids on wheat (Aslam et al. 2005). The aphid infestation can be decreased by early sowing of wheat (Acreman and Dixon 1985) because aphid infestation rises on late sown crop and reduces grain yield as compared to normal sowing (Aheer et al. 1993). Delayed sowing might be detrimental for a wheat crop if cool and sometimes cloudy weather prevails up to the end of March. Similarly, host plant resistance is one of the most vital factors which can handle aphid infestation well below the economic threshold level. Host plant resistance also lessens the chances of biotype development (Lowe 1987; Riazuddin et al. 2004). Higher concentration of allelochemicals is also reported to impart resistance against aphids by affecting development, fecundity and inherent rate of increase (Leszczynski et al. 1995). Under conditions of high aphid populations which can lead to heavy yield loss, chemicals are the only option for knocking down pest population below the economic injury level (Riazuddin et al. 2004). Many studies demonstrated that the use of various insecticides can be helpful in managing aphids on wheat (Ahmed et al. 2001; Iqbal et al. 2005). Moreover, aphids can be controlled by spraying the crop with insecticides such as Imidacloprid 200 SL, Thiamethoxam 25 WG, Clothianidin 50 WDG, Dimethoate 30 EC and Oxydemeton-methyl 25 EC. Since the aphids appear first on borders of the crop, spraying can therefore be done only on the infected strips to check their further spread. A variety of predators and parasites attack aphids and these include lady beetles spp., the parasitic wasps and green lacewings. Amongst several species of lady beetles, the seven-spotted lady beetle, *Coccinella septempunctata*, is the most common species found attacking aphids in wheat. The most parasitic wasp species are *Lysiphlebus testaceipes*, *Diaeretiella rapae* and *Aphelinus varipes*. The larvae of green lacewings, *Chrysoperla carnea*, feed primarily on aphids but are not so commonly found in wheat. These beneficial insects keep aphid populations from increasing to damaging levels.

9.2.3 Pink Stem Borer *Sesamia Inferens* Walker

Pink stem borer (*Sesamia inferens*) is a polyphagous insect that bore into the wheat stem and eats tissue making the wheat head become white. Subsequently, they bore into central shoot, resulting in the drying up of the growing point and formation of "dead heart" in young plant and "white ears" at earhead stage (Deol 2002; Beant 2012). The pest has a wide host range: *Oryza sativa*, *Triticum aestivum*, *Saccharum officinarum*, *Avena sativa*, *Zea mays*, *Sorghum bicolor* and *Eleusine coracana*. *S. inferens* is observed in regions where the rice-wheat cropping pattern is practiced. It has been reported in India, Pakistan, China, Japan, Myanmar, Borneo, Hong Kong, Indonesia, Cambodia, Ceylon, Korea, Malaya, the Philippines, Singapore, Taiwan, Thailand, Vietnam, Australasia and Pacific Islands (Gaur and Mogalapu 2018). The infestation of pink stem borer in wheat is estimated to be 5.7–11.10% (Singh 1986; Lina et al. 2012). A higher infestation is observed in zero tillage, as compared to conventional tillage (Razzaq et al. 1997; Beant 2012). The possible reason could be the presence of a higher number of infested stubbles in zero tillage plots and the pest is found to overwinter in rice stubbles. The conventionally tilled plots still reported the incidence of pink stem borer that may be due to the fact that conventional tillage did not completely destroy the rice stubbles and they remained in the field even after ploughing several times (Inayatullah et al. 1989). Also, early sown crops suffer a reportedly higher incidence of pink stem borer in comparison with late sown crops.

9.2.3.1 Biology

The adult moths of *S. inferens* are ochreous in colour, while the forewings have a red-brown suffusion along with median nervure and veins 2–5. The hindwings are whitish and the antennae of male are hairy, while those of female are simple. Larvae are the main destructors of a wheat plant and range in size between 30 and 40 mm, pink with buff and pink dorsal markings and a brown head (Hampson 1892). After damaging one tiller of young wheat seedling, they transfer to nearby tillers. However, damage is restricted to some parts of wheat fields and is not irregularly distributed. September and October account for maximum incidence of *S. inferens* (2.76–4.17%) when maximum, minimum and average temperatures range from 31.9 to 33.9 °C, 22.2 to 26.3 °C and 26.9 to 29.5 °C, respectively. The favourable conditions for attack of *S. inferens* comprise of the values of correlation coefficient (r) between the PSB incidence and maximum, minimum and average temperatures and sunshine hours of −0.19, −0.005 −0.11 and −0.27, respectively, which are non-significant at ($p = 0.05\%$); are statistically significant and show positive correlation ($r = 0.53$) with relative humidity; show average relative humidity of 80% which is favourable and a positive and non-significant correlation ($r = 0.15$) of PSB incidence with rainfall (Singh et al. 2015).

9.2.3.2 Management Strategies

If the infestation is more, spraying with quinalphos 25 EC @ 400 mL/acre is found to be effective. Invention of tolerant varieties is a boon to agriculture. Wheat varieties, DBW 17, DBW 39, CBW 38 and K 307, provided desirable tolerance to pink stem borer with damage reported of (0.75% and 1.06%), (1% and 1.94%), (1.75% and 0.94%) and (2% and 1%), respectively (Bhowmik et al. 2017). The effect of diatomaceous earth (DE), a soil-applied Si source and soluble silicic acid and a foliar applied Si source at two levels of potassium was studied for their efficacy against pink stem borer (PSB) incidence and damage in wheat. Soil application of DE @ 300 kg ha^{-1} significantly decreased the PSB incidence with the lowest per cent white ear damage and recorded the highest grain yield of 3.31 t ha^{-1} (Jeer et al. 2020). In a laboratory bio-efficacy study, minimum per cent dead heart damage with Carbofuran 36.67% was revealed, which was at par with Flubendiamide 43.33% followed by Rynaxypyr 45.50%, Thiamethoxam 46.67%, Emamectin benzoate 50.0% and Cartap hydrochloride 56.67% treated plots. The highest per cent dead heart damage was recorded with Fipronil 60.0% (Sidar et al. 2017).

9.2.4 Armyworm *Mythimna Separata* (Walker)

The oriental armyworm, *Mythimna separata* (Walker), is one of the key cereal pests (Wang et al. 2006; Jiang et al. 2014; Chang et al. 2015, 2017; Duan et al. 2017; Hou et al. 2018; Chen et al. 2019) in Australia and Asia (Sharma et al. 2002). The pest is also known with distinctive names worldwide such as southern armyworm, Chinese armyworm, paddy armyworm, sorghum armyworm, army caterpillar, ear-cutting caterpillar and paddy cutworm. Serious outbreaks have occurred in Australia, Bangladesh, China, Fiji, India, Japan, New Zealand and Thailand. In India, it is widely distributed in Indo-Gangetic plains of Punjab, Haryana, Madhya Pradesh and Uttar Pradesh (Chander et al. 2003).

9.2.4.1 Biology

Larval stage is the only destructive stage. Larvae of armyworm are tri-striped with orange, white and brown colours running the length of each side. The larvae also have a narrow broken stripe down the centre of their backs. They usually feed at night and early in the morning because they prefer shade (Hamblyn 1959). However, during the period of humidity and wet weather conditions the larvae may feed in the daytime also. They hang upside down from the slender bristles on the head (awns). The adult moths of *M. separata* are strongly built and are pale brown in colour (Farook et al. 2019). There are black spots located at the top of the four pairs of prolegs. The females lay 500–900 eggs with a record of maximum of 1943 eggs. It takes 26–38 days for complete development (Avasthy and Chaudhary 1965; Cadapan and Sdnchez 1972; Singh and Rai 1977).

9.2.4.2 Management Strategies

Numerous strategies to mitigate *M. separata* have been tested, but a few gave promising results. Out of these, one is the utilization of transgenic wheat varieties that carry two insecticidal genes, cryIA(c) and pta (Wei et al. 2008). The WeCI (wild emmer chymotrypsin inhibitor) also significantly increases the mortality rate of larvae of *S. exigua* by decreasing their fertility (Ruan et al. 2017). Another strategy includes the spray of bio-based insecticides such as Entrust® WP (spinosad 80%) at concentrations of 0.1, 0.5, 1.0, 0.001, 0.01 and 2.0 fold the lowest labelled rates and cause 83–100% mortality at day 3 against the larvae of *Dargida diffusa*. The other entomopathogenic fungi comprising of Xpectro® (*B. bassiana* GHA + pyrethrins), Xpulse®OD (*B. bassiana* GHA + azadirachtin), Aza-Direct® (azadirachtin), Met52® EC (*M. brunneum* F52) and Mycotrol® ESO (*B. bassiana* GHA) caused 70–100% mortality (0–30% survivability) from days 7 to 9 (Reddy et al. 2016).

9.2.5 Brown Wheat Mite *Petrobia Latens (*Muller)

The brown wheat mite, *Petrobia latens* (Muller), is known to be a pest of dry land wheat found in continents like Asia, Europe and North America (Bhagat 2003). Additionally, infestation is ascertained in some irrigated areas also. Substantial harm is caused by the infestation of this pest (Fenton 1951). Both adults and nymphs go after leaf plate, sheath and spikes. Serious harm is caused to the lower leaves of wheat and barley that become iron deficient (anaemia) and get dried up. Plagued plants suffer cell sap loss, exhibit a sickly yellowish/bronze look and make stipples on leaves (Bhagat 2003). The seasonal supercooling temperature of brown wheat mite in Colorado is −17 °C (Sitz et al. 2019). In keeping with the author, the best variation in supercooling purpose was seen within the spring, throughout that supercooling purpose temperatures ranged from −9.2 to −25.5 °C. Little nymphs of brown wheat mite are slightly additionally cold tolerant.

9.2.5.1 Biology

Brown wheat mites are less than 1/50 inch in size. They have a dark-brown body along with four pairs of light brown to yellowish legs. Their forelegs are twice as long as the remaining three pairs. Temperature plays a crucial role in the development of incubation stage. Female mites lay two types of eggs that hatch at 72 F (one female can lay one type of egg), that is, spherical, cherry red eggs during winters that hatch within a week and white-coloured eggs encapsulated with waxy coating and a ruffled cap during spring which do not hatch until fall (Wang et al. 1985). Therefore, mites spent their summer in dormant stage. The author also concluded that from fall to spring season there are multiple generations, each stage is of about 21 days, depending on temperature conditions. Diapause eggs require moisture for hatching, but excessive amounts were detrimental to the other stages (Cox and Lieberman 1960). The mites feed by piercing into plant cells that result in "stippling". Infested wheat plants give scorched or bronzed and withered appearance. It is observed that the activity of brown mites is found to be greatest in noon on warm days. Research suggests that a treatment threshold of 25–50 brown wheat mites per leaf in wheat, that is, 6 in. to 9 in. tall is economically warranted.

9.2.5.2 Management Strategies

A number of chemicals have been used against brown wheat mite, out of which phosphorus compounds gave the best results (Henderson et al. 1955). Furthermore, a single application of Dimethoate, Parathion, Demeton, Dasanit® (O,O-diethyl O-[p-(methylsulfinyl)phenyl] phosphorothioate), Carbophenothion, Ethion, Tranid® (*exo*-5-chloro-6-oxo-*endo*-2-norbornanecarbonitrile *O*-(methylcarbamoyl)oxime), UC 19786 (2-*sec*-butyl-4,6-dinitrophenyl isopropyl carbonate), Niagara 10242 (2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate) and Diazinon reduces the population of *P. latens* by 77% or more within 1 week after being applied (Depew et al. 1968). Emulsion sprays of 0.15% Thiometon, 0.15% Dimethoate and 0.06% Parathion at the rate of 900 L/ha and Parathion in the form of a 1.5% dust at 24.7 kg/ha effectively control the pest and produce no evident phytotoxic effects (Saxena et al. 1969). Dimethoate, Monocrotophos and Oxydemeton-methyl applied at 0.1, 0.15 and 0.1 kg toxicant/ha, respectively, give an effective control (Deol et al. 1974). Spray of Propargite 57SC (Omite) @ 1.5 mL/l of water per hectare in 500 L of water can be applied and the treatment needs to be repeated after 15 days of interval depending on the pest incidence. If rainfall greater than 0.25 in. happens, it will often help in reducing mite population and plant stress.

9.2.6 Wheat Stem Sawfly *Cephus Cinctus* (Norton)

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), is historically one of the most significant economic insect-pests of solid-stemmed cultivars of common wheat, *T. aestivum* L. (Poaceae) (Morrill et al. 1995; Beres et al. 2011; Fulbright et al. 2017) in different parts of the World (Shanower and Hoelmer 2004). *C. cinctus* is indigenous to North America and exhibits a relation with Siberian species (Ivie and Zinovjev 1996). History reveals that it was dispersed in North America because of the transportation of larval-infested straw or crown of plants (Ivie 2001). Out of 25–30 species of the genus *Cephus*, two species are established in the Northern part of America. *C. cinctus* is established in the Western United States and Canada, and *C. pygmaeus* (L.) in the Eastern United States and Canada. Merely, *C. cinctus* causes large economic losses. A model suggests that the *C. cinctus* population is growing and is predicted to increase by three times in few years in the absence of added control measures (Rand et al. 2017).

9.2.6.1 Biology

Earlier, both males and females of *C. cinctus* were considered weak fliers and rarely flew long distances. However, recent research indicates that they would be able to move as far as they need to and cover up to several miles from their site of origin (Fulbright et al. 2017). Females lay 30–50 eggs in their life span. The sawfly lays two types of eggs, that is, fertilized eggs (diploid) which produce female and unfertilized eggs (haploid) which produce male. This species has only one generation per year. Adults of stem sawfly prefer warm condition and a temperature of more than 62 °F is suitable. The adults last for 3–4 weeks.

Larval stage is the most damaging to wheat crop, as compared to any other stage of growth. Generally, eggs are laid in the second and the last developing internodes of the plant. Therefore, larvae consume the stem, hollow it within a week and then move to the basal part of the plant (Shanower et al. 2004). The major loss to the crop occurs when the larvae destroy parenchyma and vascular tissues of the plant causing a decline in photosynthesis. Severe attack happens when females oviposit first within field margin that very often results in the uniform distribution of eggs as the flight progress (Nansen et al. 2005).

9.2.6.2 Management Strategies

Insecticides have proven to be ineffective against wheat stem sawfly. Therefore, IPM (integrated pest management) and ICM (integrated crop management) techniques comprising of host plant resistance complemented with reduced tillage are helpful for managing *C. cinctus.* Significant pest suppression can be done by increasing parasitism of overwintering larvae (Rand et al. 2017). Natural enemies of *C. cinctus* are *B. cephi* (Gahan et al. 1918; Ainslie 1920), *B. lissogaster* Mues (Muesebeck et al. 1967; Somsen and Luginbill 1956), *Endromopoda detrita* (Holmgren) (Davis et al. 1955) and *Scambus detritus* (Holmes et al. 1953). Cultural control methods such as swathing, tillage, delayed planting and crop rotation are recommended for managing the pest. Using resistant genotypes with solid stem can prove to be beneficial to minimize damage to a greater extent.

9.2.7 Cereal Leaf Beetle *Oulema Melanopus* (L.)

The cereal beetle (CLB), *Oulema melanopus* (L.) (Coleoptera: Chrysomelidae), is a native pest of Europe and Asia (Philips et al. 2011) and now designated as an invasive pest in North America (Haynes and Gage 1981). It is also reported in North Western American countries (Dosdall et al. 2011). It is also present in Japan and South-Eastern Europe countries together with the Republic of Hungary, Yugoslavia, Poland and Balkan countries. Although it feeds on varied species of wild grasses and cultivated crops, its preference crops are wheat, barley and oats (Wilson and Shade 1966). In Virginia, if a cereal leaf beetle is not treated, wheat fields can suffer an average of ≈15% yield loss (Herbert and van Duyn 2009).

9.2.7.1 Biology

The adult beetle is 5 mm long, has red thorax, elytra legs and a chromatic black head. Feeding of adults typically does not always cause any economic loss to wheat crop. However, larvae of cereal leaf beetle consume parenchyma tissue of the leaf that abandons the leaf skeleton solely (Grant and Patrick 1993; Buntin et al. 2004). As a result, yield and quality of produce is affected (Wilson et al. 1964; Merrit and Apple 1969; Webster and Smith 1983). *O. melanopus* larval feeding on flag leaf can cause the highest yield losses. Although the beetle usually has only one generation per year, a second generation is additionally reported in Virginia (McPherson 1983). The life cycle of a cereal leaf beetle is typically of 46 days. Depending upon the temperature and environmental conditions, the life span of a cereal leaf beetle can be as short as 10 days and as long as 90 days (Guppy and Harcourt 1978).

9.2.7.2 Management Strategies

Although, host plant resistance has proved to be very effective against the cereal leaf beetle due to the presence of trichomes (pubescence) on the leaf surface (Wellso 1986). But, it could not be exploited to its maximum because of two reasons: negative correlation between resistance and yield and absence of diverse resistance resources (Kostov 2001). Recently, Würschum et al. (2020) identified a major quantitative trait locus (QTL) called Ppd-D1 that explains 35% of the genotypic variance of cereal leaf beetle resistance. Thereby, they concluded genetic control underlying insect resistances in small-grain cereals. Besides this, virtual elimination of *O. melanopus* injury can be seen by the early application of λ-cyhalothrin (Buntin et al. 2004). Malathion, Methomyl, Carbaryl and Spinosad when applied after eggs hatching effectively control its larval attack. Calendar-based insecticide application adopted by farmers in Mid-Atlantic States as a management tactic proved very effective against the attack of cereal leaf beetle (Ihrig et al. 2001; Herbert and van Duyn 2009). Two essential oil formulations viz., *Rosmarinus officinalis* with *Cymbopogon citratus* and *Pelargonium graveolens* with *Thymus vulgaris* using the encapsulation procedure show 100% mortality within 24 h of treatment (Skuhrovec et al. 2018). Biocontrol species such as *T. julis*, *Diaparsis carinifer*, *Lemophagus curtus* and *Anaphes flavipes* are parasitic to larvae and eggs of *O. melanopus* can be used (Haynes and Gage 1981; LeSage et al. 2007; Evans et al. 2015).

9.2.8 Pod Borer *Helicoverpa Armigera* (Hubner)

H. armigera is a polyphagous pest that can attack more than 172 plant species from 68 different families including that of wheat (Kranthi et al. 2001; Singh et al. 2002; Chander et al. 2003; Liu et al. 2008 Cunningham and Zalucki 2014; Agrawal et al. 2015; Gregg et al. 2019). It is reported from Asia, Europe, Africa, Australia and the Pacific Islands (Tay et al. 2013; Czepak et al. 2013). Just a single caterpillar of *H. armigera* per tiller can cause 13.98% of yield loss (Saleem and Rashid 2000). Higher infestation is noticed in the fields where cotton-wheat rotation is followed. The pest generally infests the crop in the month of March-April.

9.2.8.1 Biology

The larval stage causes damage to wheat crop. Pod borers complete eight generations per year. The life span of *H. armigera* is 38–45 days with egg period of 2–4 days, larval period of 15–20 days and pupal period of 10–14 days. The female of *H. armigera* lays yellow spherical eggs on leaf which varies from nearly 600 to 800 in number. The larval period comprises of six larval instars. The freshly hatched larvae feed on green leaves and in the later stages, the larvae consume grains in earheads. The mature larvae are brownish or pale green in colour. They have brown lateral stripes and a different dorsal stripe. The larvae also show colour polymorphism (King 1994). Afterwards, the fully grown larvae pupate in soil. The colour of the pupa is darkest brown. Pod borer adult moths are stout-bodied, are 14–19 mm long and have a wing span of 3.5–4 cm. Forewings are black or dark-brown in colour and have kidney-shaped markings near the centre. Hind wings have a greying band on the outer margins and are cream-white in colour. Males and females differ in colour, as males are yellowish brown and females are orange brown. The rate of infestation on earhead is 15%, but grain damage on infested earheads is about 3.9%.

9.2.8.2 Management Strategies

Intercropping can reduce the attack of gram pod borer. Spraying quinalphos 25 EC 400 ml/acre is an effective treatment for *H. armigera.*

9.2.9 Gujhia Weevil *Tanymecus Indicus* Faust

Tanymecus indicus Faust (Coleoptera: Curculionidae), commonly known as "Gujhia Weevil", is a pest of wheat in India, Myanmar and Ceylon (Gaur and Mogalapu 2018). It was first discovered in Bengal in 1894 by Faust. It belongs to the subfamily, Brachyderinae, of the family Curculionidae (Pajni 1989).

9.2.9.1 Biology

Gujhia weevils have one generation per year. Leaves and tender shoots of the wheat plant are mostly attacked by the weevil. It harms the plant by cutting germinating seedlings above the ground at the plumule region (Srivastava and Lal 1973). The weevils also destroy sown seeds which then do not germinate and sometimes resowing is necessary (Singh and Guram 1960). Weevils are nearly 4.5–7.5 mm in length, 1.75–2.75 mm in width and are greyish black-brown in colour. They have oblong forewings, more or less triangular hind wings, leathery prothorax, long round sides and a faint trail of a central ridge on the anterior half. Adults of *T. indicus* weevil mainly damage the wheat crop because all the other stages, from egg laying to pupae, are spent in soil. Females lay around 50 eggs under crevices which reside for 6–7 weeks.

The grub time period is of 10–18 days and pupal time period is of 7–9 weeks. Adults emerge in June or July (after monsoon) and remain active from June to December. For the rest of the year, they remain in larval or pupal diapauses in soil.

9.2.9.2 Management Strategies

The adult weevil can be controlled by the dust application of Malathion 5 D @ 25 kg per ha. The fields can be ploughed in the summer to expose and kill the pupal stage of the weevil.

9.2.10 Wheat Midge *Sitodiplosis Mosellana* (Géhin)

Throughout Canada and the USA, wheat midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), is a serious pest of *Triticum aestivum* L. which brings about considerable damage (Poaceae) (McKenzie et al. 2002; Chavalle et al. 2015; Echegaray et al. 2018; Olfert et al. 2020). It is also known with the name orange wheat blossom midge. In the Northern Hemisphere, it is a periodic pest of wheat. One, 2, 3 and 4 larvae per kernel result in significant infestation by which the average decrease in crop yield rises to around 30%. Losses in the total gross revenue are estimated to be nearly $30 million (Olfert et al. 1985).

9.2.10.1 Biology

Two important factors on which the development of *S. mosellana* highly depends are soil moisture and temperature. In a sufficiently moisturized soil, larval diapause can be terminated, while if the soil is dry, the larvae can remain in diapause for 1 year. Furthermore, the larval termination occurs in two phases: for the first 3 months, the larvae need a cool temperature and for another 5–6 weeks, the larvae enter into a moisture-sensitive phase. In the latter, pupation and adult emergence occur. The adult is around 2–3 mm in length, with a large black pair of eyes, three large pairs of legs and oval-transparent wings. Environment preference of adults is humid crop canopy where females can lay eggs on newly emerging spikes. The attack of *S. mosellana* can be observed on all parts of spikes of the wheat plant, whereas larval attack is generally on small seeds (Lamb et al. 2000). Wheat midge larvae damage the grains by shrivelling them.

9.2.10.2 Management Strategies

Nowadays, sustainable agriculture is of primary concern across the World. Biological control methods are one of the most important techniques that benefit the farmer as well as do not harm the environment. Amongst these, there are parasitoids that effectively control the *S. mosellana*. In Saskatchewan, Canada, 31.5% of wheat midge is controlled by releasing *Platygaster tuberosula* (Olfert et al. 2003) and *Macroglenes penetrans* (Kirby) (Hymenoptera) (Olfert et al. 2008).

Incorporating resistance in wheat is another phenomenon. It contributes to the reduction of wheat loss in years. Cultivar RL5708 shows a lower number of damaged seeds associated with dead *S. mosellana* larvae (Barker et al. 1996). Besides these, common insect-capturing techniques such as sex-pheromone baited traps and yellow sticky traps can also be used against wheat midge. Pheromone traps are effective against male adult midges due to a large surface area, whereas small yellow sticky traps capture more female midges (Jorgensen et al. 2020). Biopesticide, jasmonic acid (JA), effectively reduces larvae of *S. mosellana.* The level of kernel damage reduces as well as wheat produces higher yields (Chavalle et al. 2015; Shrestha et al. 2019). The foundation of future control of wheat midge can be the identification and characterization of sweet sorghum grain protein (SSGP), as transcripts provide a comparative analysis of insect affecting agents from related species (Al-jbory et al. 2018).

9.2.11 Hessian Fly *Mayetiola Destructor* (Say)

It is considered by some that around 16 grass species, most pertaining to tribe Triticeae, serve as a host of Hessian fly (Zeiss et al. 1993; Harris et al. 2001). The Hessian fly, *Mayetiola destructor* (Say) (Diptera: Cecidomyiidae), is a serious pest of wheat (*Triticum* spp. L.). It contributes to reducing crop yields across the globe (Schmid et al. 2018; Campos-Medina et al. 2019; Zhao et al. 2020; Liu et al. 2020). The origin of *M. destructor* is a fertile crescent region in the middle Eastern Europe, North America, Northern Africa and New Zealand (Stuart et al. 2012). The fly causes injury to the wheat plant by forming dark almost blue-green foliage colour and stunting its growth (Whitworth et al. 2009).

9.2.11.1 Biology

Hessian fly eggs are identified by their orange tone, small size and elliptical shape (Flanders et al. 2013). The colour of adults of *M. destructor* is brown or black, with females at times appearing red-brown (VanDuyn et al. 2003). The laying of eggs takes place in the grooves on the upper side of a wheat plant leaf. Generally, it takes 3 to 12 days for the eggs to hatch. The favourable temperature for hatching is 50–85 °F (10–29 °C) (McColloch 1923; Packard 1928). In total, there are three larval instars, first instar (0.56–1.70 mm long), second instar (1.70–4.00 mm long) (Gagne and Hatchett 1989) and third instar larvae. Development of the third instar larvae and pupae occurs in the cuticle of the second instar larvae. This stage is known as the flax seed stage because of hard and dark-brown colour of the cuticle. Neonate larvae require up to 12–24 h to move from egg to the site. Meanwhile, they establish a feeding site on the stem under the leaf sheath. The chances of larval mortality are at its maximum during this period because of high rainfall, relative humidity, cold and wind (Packard 1928; Hamilton 1966). Larval stage causes maximum damage to the wheat plant. Virulent larvae secrete glycoside hydrolase MdesGH32 extra-orally that localizes within the leaf tissue. With the help of strong inulinase and invertase activity, MdesGH32 aids in the disintegration of the wheat plant cell wall inulin polymer into monomers and converts sucrose into glucose as well as fructose. In this way, nutrient sink formation occurs and the plant becomes susceptible (Subramanyam et al. 2021).

9.2.11.2 Management Strategies

The phenomenon of identification of target-specific genes conferring resistance is becoming popular day by day. In the case of Hessian fly also, researchers have identified few genes that effectively control the infestation of the fly. Amongst these, H26 and H32 genes are suitable against biotype "L" of the Hessian fly. The gene H32 was isolated from synthetic wheat variety such as amphi-hexaploid wheat, W-7984, which was made from the durum "Altar 84" and *Aegilops tauschii* (Cox et al. 1994). Integrated pest management is another management technique and is considered as an ideal control measure for the Hessian fly. It encompasses resistant plant cultivars, fixing planting dates, destroying green bridges (volunteer wheat) and suitable insecticide seed treatment (Whitworth et al. 2009; Royer et al. 2015; Schmid et al. 2018). Recently, two new *M. destructor* quantitative trait loci have been identified, namely, H35 and H36 as well as single nucleotide polymorphism (SNP) markers which have also been invented, for instance, SD06165 (Zhao et al. 2020).

9.3 Conclusion and Future Prospects

The post-green revolution period has already witnessed an increase in pest problems, both in the number of insect species as well as in their severity. As per an estimate, around 40% of the world's food supply is being affected by pests and it has been observed that climate change is affecting the biology, distribution and outbreak potential of pests in a vast range of crops and across all land uses and landscapes. Replacement of older tall varieties with dwarf high-yielding ones, expansion in irrigation facilities and indiscriminate use of increased rates of agrochemicals in recent years with a view to increasing productivity have resulted in heavy crop losses due to insect-pests in certain crops. This scenario has occurred because of pest resurgence, secondary pest outbreak, eradication of natural enemies and development of insecticide resistance. The damage by insect-pests can cause enormous grain yield losses, if not managed in time. Earlier, wheat crop which was considered a pest-free crop is now being damaged by nearly half a dozen insect-pests from seedling to maturity stage. Host plant resistance targeting towards the development of resistant cultivars is one of the important pest management strategies to reduce the climate change impact on crop production. Efficacy of current pest management techniques can be re-evaluated to determine the most effective way to manage the pests. Further timely pest monitoring and practicing integrated pest management practices can reduce the insect-pest damage. The influence of climate change on insect-pest abundance and distribution should be studied and focus should to given to develop mitigation and adaptation strategies, keeping in view the recurrent pest outbreaks. The effect of climate change on host plant resistance expression and assessment of various pest management technologies under diverse environmental conditions should be determined. Thus, there is an urgent need to develop strategies to climate-smart pest management strategies under the changing climate scenarios.

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Technological Innovations for the Management of Insect-Pests in Stored Grains

10

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10.1 Introduction

Insects have been associated with mankind since centuries together causing large scale destruction to food through eating, disease problem, contamination of food through their excreta, skin castings, etc. (Scott 1991). The problem of food destruction by insect-pests is more so under storage facilities, because under such conditions insects get ample food due to bulk storage, do not have to move for search of food, and are protected from itches of climatic instabilities. The presence of insects in storage reduces both quality and marketing value of grain and in some countries like Britain, the grain is being discarded even at minimal presence of insect-pests (Pinniger et al. 1984).

Keeping in the damage caused to stored grains by insect-pests, different control measures have been employed over the years for same purpose. Involvement of sun drying before transferring to a granary for storage, picking, slapping and crushing, use of charcoal as a desiccant, etc., are some of the measures used since long. Besides these measures, early attempts of storage grain pests relied on the use of wood ash, fumigants (Levinson and Levinson 1989), utilization of sieving or flotation to remove infested grains employed by Indian and Chinese farmers, biological plant resources such as neem leaves or insecticides derived from plants as mentioned in oldest manuscripts in India. In the late seventeenth and early eighteenth centuries, botanical insecticides like pyrethrum, derris, and herbal tea tobacco leaves were rediscovered for storage pests particularly so in Europe. During

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the beginning of twentieth century, a thriving in the development of insecticides and application equipment was observed and the science of insect check advanced securely through the first 40 years of the twentieth century with the development of synthetic organic pesticides after World War II.

However, realizing the problems and side effects of synthetic chemical insects, researchers, hence, began to develop alternative technological innovations as well as improving existing methods and basic research (Hagstrum and Athanassiou 2019). Keeping the undesirable ramifications of insecticides in view more so in storage commodities, a broad professionalism and knowledge is always necessary as reckless use of pesticides under storage caters to severe health, financial, and esthetic problems. The technological innovations for management of storage insect-pests involve new processes and products that are significantly different from before offering specific advantages. The use of insect growth regulators, bio-rational materials as pheromones, modified atmosphere applications such as more CO2 and/or less O2 for little times, hermetically storing of food grains, sensing technology for observing the value of grain and for identifying the pestilence of deposited grains (Kaushik and Singhai 2018) are some of the technological innovations for the management of stored grain insect-pests. The objective of this chapter to discuss and integrate different technological innovations that have evolved over the years for successfully managing of stored grain insect-pests.

10.2 Innovative Technological Interventions for the Management of Insect-Pests of Stored

10.2.1 Hermetic Technology

It is always better to encourage such measures that minimize the factors responsible for storage grain damage by maintaining hygiene and sanitation and demand least investment on the part of farmers. For example, the use of Hermetic Storage (HS) technology has become a significant alternative to other storage methods that protect products from insects and mold. This know-how is also known as closed storage, sealed storage, or assisted airtight storage. The application of hermetic technology has been widely encouraged for a long duration storage of grains. It involves the protection of stored food without application of chemicals and lowers the use of refrigeration for control of insets besides maintaining quality of stored products. It works on the simple of de oxygenation by preventing the air from entering and leaving the container. As result respiratory metabolism of insects and grain itself lowers the oxygen content and increases the carbon dioxide content to a level where aerobic breathing of damaging insects is lowered. Airtight storage containers such as metal silos and super grain bags made from polyethylene can help farmers to reduce post-harvest losses. The only disability attached with metal silos is that they are quite expensive but very effective. Compared to conventional reinforced concrete (RC) and galvanized steel silos (GS), grain silos are suggested for grain storage in humid tropical regions. Nevertheless, plastic structures are preferred for flexibility, transportability, ease of assembly, simplicity of operation and maintenance, and durability.

10.2.2 Monitoring Technology

Stored grain insect damage can be minimized only if the infestation is quickly detected followed by the application of proper control measures. Among the living and non-living factors which upset grains/seeds in storage, insect acts as a chief part in the corrosion of grains/seeds instigating together qualitative and calculable damages. Frequently the existence of insects in store stocks is sensed only when they are moving and flying nearby, by which stage massive damage and population build-up of insects might have ensued. Hence, well-timed uncovering of the stored grain insects will benefit to avert substantial harms.

Different techniques are being employed for detection and decision making in storage pest management as discussed under different headings.

10.2.2.1 Grain Probe Traps

Grain probe traps are tubular conduits with punctures in the superior section through which insect descend into the trap and are incapable to move out because of the shape of the container. They have a short effective life since their surfaces are easily covered with dust. Therefore, they must be draped from the store rooftop, to suspend above or among stacks or loads of stored grains.

10.2.2.2 Sticky Traps

Sticky traps are smeared with an adhesive material (such as petroleum jelly or polybutene gel generally retailed as bird repulsive) that inhibits insects from exiting after landing on it.

10.2.2.3 Pheromones

Among the various technologies that have been developed or are being developed for perceiving insects of stored-products, the most capable are pheromones and/or food attractants (Table 10.1). They are mass produced accessible for more than 35 species of stored-product insects. They can be used for monitoring as well as control of storage pests. The man-made pheromones are typically hemmed in slow release dispensers proficient of liberating pheromone for weeks or sometimes months. By employing the pheromones in minute quantities through various kinds of traps mainly adhesive, funnel, corrugated paper, and plastic grain probe, the insects are successfully trapped. Various designs of traps for different kinds of pests such as moths and beetles pervading stored products have been advanced, generally on a realistic basis. Generally the pheromone traps are used in mass trapping and mating disruption procedures. Mating disruption dispenser strips technology is widely used for Indian Meal Moth.

Pheromone baits advanced for species having short-lived adults have been confirmed more beneficial. The bait for the lesser grain borer (*Rhyzopertha*

Table 10.1 Pheromone components for storage insect pests

Family	Pheromone component
Dermastidae	
Trogoderma	(Z)-14-Methyl-8-hexadecen-I-ol
Attagenus	(E,Z)-3, 5-Tetradecadienoic acid
Anthrenus	(Z)-3-Decenoic acid
Anobiidae	
Stegobium	2,3-DihYdro-2,3, 5-trimethyl-6 (l -methyl-2-oxobutyl)-4H -pyran-4-one
Lasioderma	4,6-Dimethyl-7-hydroxynonan-3-one
Bruchidae	
Acanthoscelides	(E)-(−)-Methyl-2,4,5-tetradecatrienoate
Bostrichidae	
Rhyzopertha I-Dominica	Methylbutyl (E)-2-methyl-2 pentenoate (dominicalure I) and I-methylbutyl (E)-2,4-dimethyl-2- pentenoate (dominicalure 2)
Tenebrionidae	
Tribolium	4,8-Dimethyldecanal
Curculionidae Sitophilus oryzae	4-Methyl- 5-hydroxy-3-heptanone
Gelechiidae Sitotroga	(Z,E)-7,II-Hexadecadien-I-ol acetate
Pyralidae Ephestia elutella Plodia interpunctella Cadra cautella Anagasta kuehniella Cadra figulilella	(2.E)-9,12-Tetradecadien-I-ol acetate (TDA)

dominica) also has given decent outcomes. Food lures mainly consisting of an oil lure of oat oil, wheat germ oil extracts and mineral oil, wheat germ oil extracts and mineral oil are used for stored-product insects of various species having long-lived adults and various larvae. These baits may be used alone or in combination with pheromones. Overall, baits have a smaller active range than pheromone lures. They can be employed to improve the efficiency of pheromone traps for flour beetles (*Tribolium*) and to tempt *Trogoderma*, *Attagenus*, and *Anthrenus* larvae (Burkholder and Ma 1985).

However, various studies have reported success in the control of the almond moth, Cadra cautella (Walker), in the USA; P. inter-punctella in a storage room for vegetable and flower seeds in France; the Mediterranean flour moth, *Ephestia kuehniella* Zeller, in some Italian mills; the cigarette beetle, *Lasioderma serricorne* (F.), and *P. interpunctella* in two food ware-houses in Hawaii; *L. serricorne* in tobacco stores in Greece, in a cigarette factory in Portugal and in a Hawaiian bakery; punctella in a storage room for vegetable and flower seeds in France; the Mediterranean flour moth, *Ephestia kuehniella* Zeller, in some Italian mills; the cigarette beetle, *Lasioderma serricorne* (F.), and *P. interpunctella* in two food ware-houses in Hawaii; *L. serricorne* in tobacco stores in Greece, in a cigarette factory in Portugal and in a Hawaiian bakery.

10.2.2.4 Light Traps and Visual Lures

Light Traps are utmost effective at perceiving moth invasions since the grownups are enticed to light when they vacate the produce so as to hover and mate. Ultraviolet (300–400 nm) and green light (500–550 nm) are the most attractive wavelengths to storage pests. Similar to light traps, visual lures are either lights that appeal insects from the dusky/faintly lit environs (usually fluorescent, incandescent, and ultraviolet lights) or they are colored substances that are good-looking due to their definite reflectance and shapes that stand out compared to a complementary background. Electrical cutters are positioned in dusky lit ranges where their light is not visible outdoors such that it does not lure insects into the building.

10.2.2.5 Berlese Funnel and Acoustical Methods

Berlese funnel is based on the norm that insects passage away from heat. Acoustical methods involve sound (insect feeding sounds) to automatically monitor both interior/exterior insects that devour on grains (Flinn et al. 1998).

10.2.2.6 Electrical Conductance

Alternative method in which conductance is checked by calculating the voltage across the kernel is the electrical conductance. Here, in a two-resistor and voltage-divider circuit of the single kernel description system, kernel functions as one resistor. Nevertheless, it is slow and inexact in spotting infestations of insect-pests.

10.2.2.7 Machine Vision

Machine vision is another technique consisting of advanced integrated machine vision software. It involves the use of a monochrome CCD camera and a personal computer. Comparisons are drawn between the photographic print of the illustrative model with individual grain kernels. The X-ray imaging detects both interior and exterior insects and capable to perceive both conscious and lifeless insects within the grain kernels, except it cannot detect insect eggs.

Utilization of wandering actions of the insects has led to advancement of devices by TNAU that assist in apt revealing of insects in stored produce thereby helping in their timely control. Various such devices developed by TNAU include probe trap, pit fall trap, indicator device, automatic insect removal bin, UV-light trap technology, and many more. Such devices have been confirmed with state and national appreciations and have been extensively employed in many places. In addition to above mentioned devices, a “KIT” enclosing models of all the devices along with a CD-Rom about the devices and how to use them are being used at length. This device has been christened as “TNAU-Stored Grain Insect Pest Management Kit.”

10.2.2.8 Detection of Parasitized Stored Products

An innovative technology (Panford 1987) recognized as near-infrared spectroscopy (NIRS) was employed to sense and categorize the insect-pest in stores such as distinguishing between unbitten weevil larvae and those nibbled by wasps in wheat (Burks et al. 2000). This technology is founded on the norm that the quantity of light absorbed by ingredients is subject of number of molecules of specific constituents. NIRS provides the numerical figures (Murray and Williams 1987) about the quantity of chemical constituents such as water, oil, starch, sugar, or protein in agricultural products. In NIRS principle absorptions quite often fall in the mid-IR region (2500–150,000 nm), while first, second, and third absorptions follow in the NIR region (700–2500 nm).

10.2.2.9 Detection of Early Grain Spoilage

It is quite essential to sun-dry the harvest to safer moisture contents, otherwise there is every possibility that commencement of fungal action can end up in heating of the stored grain and eventually end in unprompted heating and widespread damage of the grain, besides production of certain fungal toxins which precludes such grains to be consumed either by animal or humans. As such it is highly indispensable to perceive such fungal worsening at an early stage in stored cereal grains. The employment of Electronic nose technology offers such opportunity. It encompasses differentiating among grains populated by mycotoxigenic and non-mycotoxigenic species which thus aids in refining prevailing management of grain stores. Substantial losses and grain downgrading can also be prevented because such technology allows corrective methods to be more efficiently applied. There are many secondary fungal metabolites such as mycotoxins that are prepared by numerous main phyto-pathogenic and food decaying fungi including Aspergillus, Penicillium, Fusarium, and Alternaria species and many more and are related with stark toxic effects to vertebrates. The adulteration of foods and animal feeds with such mycotoxins is a universal misfortune (Kabak et al. 2006) and therefore catering of this problem needs further study.

10.2.2.10 Sensing Technology

In order to sense the worth of grain and identify insect invasion in stored grain, an automated monitoring technology known as sensing technology is used. The data processing which is the supreme step in sensing technology is achieved through methods like neural network, machine learning algorithm, statistical analysis, pattern recognition, etc. The data attained in these techniques are used to calculate impurity of grain or to categorize insects. For real time observing of insects in stored grain, sensor data can be used using sensor network. Different types of sensing technologies such as environmental sensing, acoustic sensing, odor E-nose sensing, image sensing are being employed to spot contamination in grain (Neethirajan and Jayas 2007).

Environmental Sensing

In this type of sensing, surplus of CO2 in grain specifies emergent spoilage of stored grain. Due to insects feeding and respiration, heat and moisture are produced leading to grain spoilage. These insects depend on temperature and moisture level for their survival and reproduction.

Acoustic Sensing

During flying, feeding, and moving, insects produce various sounds and vibrations. Such sounds and vibrations are used in Acoustic technology. Amplification and filtering of sound generated by concealed insects inside the grain can be sensed acoustically by this technique. The level of infestation can be adjudicated by this technology through the evaluation of occurrence or lack of insects, larva, assessing the population density of insects inside the grain mass.

Odor Sensing

A range of sensors and software employed for data processing and pattern recognition for identifying odor form the basis of this technology. The main advantage of this technology that singles out it is that it recognizes odor which cannot be credibly perceived by human nose as well. The classification of grain such as good, musty, moldy, and burnt based on odor (Jonsson and Winquist 1997) is done using this type of sensing.

Image Sensing

It is a wireless self-directed monitoring system which intermittently arrests images of the trap contents. Such images are sent distantly to a control station and are used for assessing of the total of insects found at each trap. Depending on insect strength, a grain storekeeper can devise when to start grain protection and in which particular area. The failure to delineate precise positioning of infestation caused by insects in stored grain is the chief disadvantage linked with above sensing technologies. This drawback can be rectified by using image sensing technology.

10.3 Regulatory Technology

10.3.1 Ionizing Irradiation

Ionizing radiations are essentially the electromagnetic waves or particles that carry enormous energy to detach electrons from the atoms or molecules so as to ionize them. In order to control insects in grains, ionizing radiations such as gamma rays and beta radiation are usually used. However, the use of beta rays is generally harmless and at ease to employ because they can be switched on and off while shielding (Fields and Muir 1996) is prerequisite in humans. The instant death to stored product insects fluctuates depending on the dose of irradiation. For example, rusty grain beetles and saw-toothed grain beetles require lower doses (Banks and Fields 1995), while grain mite needs an ample dose. The biggest advantage associated with this technology is non-residual effect of otherwise chemical insecticides. Besides it is effective against all stages of insects. Although such sterilized insects will not do much damage to grain, the grain will carry on to appear to be plagued and a grain buyer will always find himself in dilemma whether to buy or not such grains because of presence of such sterilized insects.

10.3.2 Biological Control

There is vast list of biological enemies enlisted in various insect families such as Braconidae, Ichneumonidae, and Bethylidae that have the full potential to manage the insect pests of stored commodities. The typical examples were biological control agents have been used for stored insects including anthocorid bug, *Xylocoris flavipes* (Reuter) for control of stored commodities pests such as *Tribolium castaneum*, *T. confusum* (Rahman et al. 2009), use of egg parasitoid *Trichogramma pretiosum* in peanut warehouses for suppression of Indian meal moth, etc.

10.3.3 Ozonation

Ozone a known sterilant can be employed for controlling insects in food products at low levels usually not more than 45 ppm. It is produced by UV-light and electrical discharges in air. However, high instability and rapid conversion to molecular oxygen makes this technology disadvantageous. Hence, vigorous research is demanded to ensure ozonation as a promising quarantine treatment for controlling concealed pests in storage grains (Hollingsworth and Armstrong 2005).

10.3.4 Least Chemical Utilization

Most of the non-chemical methods may not provide satisfactory insect control when used at individual level. Thus, to obtain satisfactory results, the use of chemicals has become mandatory. However, due to shifting of chemical use from less toxic natural pyrethrum to manmade and possibly hazardous neurotoxins, clues to several environmental, societal, and monetary problems is mandatory. Moreover, several stored-grain pests have also developed resistance against frequently applied insecticides. Resistance in *Trobolium castaneum* against lindane and malathion in Africa and resistance in *Rhyzopertha dominica, T. castaneum*, *Sitophilus oryzae* against phosphine are some of the known examples. However, now-a-days several harmless juvenile hormone equivalents, diatomaceous earth, and spinosyns are being used. Methoprene, hydroprene, pyriproxyfen, chlorfenapyr, and diatomaceous earth are currently registered and marketed commercially and spinosad has been formulated and registered for use on grain.

10.3.5 Less Harmful Insecticides

The servicing of residual insecticides has advanced from less harmful natural pyrethrum to manmade and possibly dangerous neurotoxins. Among these include harmless juvenile hormone analogs, diatomaceous earth, and spinosyns. Usefulness of alternative insect growth regulator (novaluron), an innovative spinosyn (spinetoram), and neonicotinoids (imidacloprid and thiamethoxam) are in research trials for elucidating their use for controlling of stored grain pests.

10.3.6 Use of Nano-technology

A noteworthy potential in management of insects and pathogens through controlled and targeted delivery of insecticides especially in stored grains can be achieved by the use of nanotechnology (Routray et al. 2016; Kashyap et al. 2020). Of late it has developed at a rapid pace to provide cost effective solution to growing stored grain pest problems. It is assumed that the use nanoparticles will surely transform agriculture including pest management (Bhattacharyya et al. 2010). New pesticides, insecticides, and insect repellants are produced through nanoparticles and this technology can also carry DNA and other desired chemicals against target insect pests (Torney 2009). There are numerous examples where nanotechnology has been employed for the control of stored pests. For example, control of *Tribolium castaneum* Herbst (Yang et al. 2009) through nanoparticles loaded with garlic essential oil, increasing toxicity of imidacloprid through nanotechnology against *Martianusder mestoides* Chevrolat (Guan et al. 2008), use of silicon dioxide against *Callosobruchus maculatus* (Rouhani et al. 2012), and combating pests of stored maize using silicon dioxide-nanoparticles (El-Naggar et al. 2020), etc. The potential applications for the control of stored grain pests are many; however, further studies are demanding for their ecofriendly synthesis.

10.3.7 Predictive Models

In order to predict population growth, age structure, and spatial distribution of stored insects, computer-based simulation models are used. These models can predict population buildup of 14 species of stored-product insect pests and 4 species of natural enemies. These predictive models are employed in expert systems for making optimal IPM recommendations.

10.4 Conclusion

Retardation of insect-pest growth and maintaining of quality of food under storage demands the advanced technologies and intensive studies. For the safe and convenient storage, the use of hermetic technology has to be encouraged as it abstains to use pesticides and other chemicals besides being sustainable and environmentally safe. This technology has allowed storage of various commodities ranging from conventional grain bag size to many thousands of tonnes. For the economical and market-based price, advanced scientific structures ensure grain infestation control and storage of food for longer duration of time without deterioration by the insect-pests. The advanced storage structures provide the opportunity of harnessing higher price during offseason when there is actually the deficiency of such grains in the market. The promising use of pheromones, X-ray imaging, and ultraviolet and green light lights ensure the increased catch in traps. The employment of near-infrared spectroscopy (NIRS) for the classification and utilization of ionizing radiations to cause death of storage insects are the encouraging innovations as they are effective against different insects and are non-residual in nature. The utilization of sensing technology for monitoring of quality of grains under storage is quite promising, rapid, and cost-effective. The detection of early grain spoilage through electron nose technology and computer-based modeling to foresee population growth of insects offers new opportunities to refine prevailing management of grain stores. The utilization of insect growth regulators and equivalents and less dependence on residual chemicals are accessible for stored-product uses, and their use could surge in the near future.

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Modern Approaches for the Management of Cereal Cyst Nematodes in Wheat and Barley

11

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11.1 Introduction

Wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare*) are among the most essential cereal food grain crops from the Poaceae family. Wheat is grown on ~218 m (million) ha area globally. With 772 m tonnes of production, it is used as a staple food by more than 2 billion people worldwide. On the other hand, barley is produced worldwide on 47.92 m ha with a global production of 141.42 m tons (FAOSTAT 2019). Wheat is the primary staple food crop, while barley is vital for the beverage industry (Giraldo et al. 2019). Cereal crop yields are affected by several abiotic and biotic stresses. Among the biotic stresses, plant-parasitic nematodes (PPNs) have emerged as a serious inhibiting factor in cereal production due to input-intensive agricultural practices and changing climatic conditions. Nematodes are suggested to reduce the global yield of small grain cereals by approximately 10% per annum, which is equivalent to 1.5 billion metric tons (Smiley et al. 2017).

The Cereal Cyst Nematodes (CCNs) are a group of 12 closely related species from the genus *Heterodera* and cause economic yield loss to wheat cultivation worldwide including North Africa, China, India, Australia, West Asia, America, and several European countries. The most commonly reported species is *Heterodera avenae,* which readily prolifers in rainfed cereal monocultures. However, at least two other species, *H. filipjevi* (yield loss documented in Turkey) and *H. latipons* are also reported from cereals. In India, *H. avenae,* commonly known as "molya disease," has been reported from Delhi, Haryana, Himachal Pradesh, Jammu and Kashmir, Madhya Pradesh, Punjab, Rajasthan, and Uttar Pradesh. A recent estimation showed that *H. avenae* could cause up to 28.5% yield loss in wheat, amounting to USD 122.25 m in monetary losses in just the Rajasthan and Haryana states.

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Fig. 11.1 A patch of stunted and yellowish wheat plants infected with cereal cyst nematodes

Early symptoms of cereal cyst nematodes appear as random pale green patches in field with lower leaves becoming yellow with fewer tillers (Fig. 11.1). Infected plants show stunted growth and uneven patches. Infected wheat roots acquire a typical bushy-knotted appearance with characteristic elongation of primary roots. In contrast, infected barley roots are not much affected, but sometimes excessive branching is observed. Young adult females are off-white colored and turn dark brown with maturity.

This chapter will discuss the available traditional and modern management approaches suitable for cereal cyst nematodes.

11.2 Nematode Problems of Wheat and Barley in India and the World

Wheat and barley are known to be infested by various plant parasitic nematodes (Table 11.1). Among the nematodes listed in the table, *H. avenae* is the major nematode infesting wheat and barley (Vaish 2017), while seed gall nematode (*Anguina tritici*) is only confined to isolated pockets (Khan 2015).

Table 11.1 Distribution of wheat infesting nematodes in world, including India

Nematode	Scientific name	Distribution	References
Cereal cyst nematode	*H. avenae*	Cosmopolitan distribution in all wheat growing area of the world including India	Donald et al. (2017)
	H. latipons	Mostly confined to Mediterranean region, prevalent in Syria, Israel, Turkey, Cyprus, Libya, Italy, and Northern European countries	
	H. filipjevi	India, Russia, Sweden, Norway, Turkey, Greece, Tajikistan	
	H. hordecalis	Britain, Sweden, Germany	
	H. zeae	India, Pakistan, Iraq	
Root lesion nematodes	*P. thornei*	India, Yugoslavia, Australia, Canada, Mexico, Morocco, Israel, India, Turkey, Algeria, Italy	
	P. neglectus	India, North America, Turkey, Australia	
	P. penetrans	India, Canada	
	P. pratensis	Azerbaijan	
Root-knot nematodes (RKNs)	*Meloidogyne naasi*	Belgium, Britain, France, Germany, Iran, Netherlands, USA, Yugoslavia	
	M. artiellia	Spain, Italy, France, Greece	
	M. chitwoodi	Australia, Mexico, South Africa	
	M. graminis	USA	
	M. triticoryzae	India	
Stem nematodes	*Ditylenchus dipsaci*	Brazil, Argentina, Europe, USA, Canada, Australia, North and South Africa	
	D. radicicola	Britain, Netherlands, Poland, USA, Russia, Germany	
The seed gall nematode	*Anguina tritici*	India, Azerbaijan, North Africa, Turkey, Pakistan, Iraq	
Stunt nematodes	*Tylenchorhynchus nudus, T. vulgaris* and *Merlinius brevidens*	USA, India	
Stubby root nematodes	*Paratrichodorus anemones* and *P. minor*	USA	

(continued)

Table 11.1 (continued)

Nematode	Scientific name	Distribution	References
Pin nematodes	*Paratylenhchus spp.*	Turkey	
Other minor nematode problems	*Rotylenchus unisexus, Rotylenchulus parvus, Scutellonema dreyeri, Scutellonema brachyurus, Paratylenchus minutes, Criconemoides, Xiphinema sp., Criconema, Dorylaimellus, Geocenamus, Hemicycliophora, Longidorus, Helicotylenchus, Paratylenchus, Pratylenchoides, Quinisulcius, Paralongidorus*	Specific to some regions	Nicol and Rivoal (2008), Smiley and Nicol (2009)

11.3 Traditional Approaches for the Management of Wheat and Barley Nematodes

Although cereal cysts nematodes and other wheat and barley infesting nematodes are responsible for the considerable yield losses, they are still ignored by plant breeders and policymakers. This ignorance stems from improper quantification of losses due to the absence of proper detection and diagnosis of infestation symptoms in field conditions. These nematodes slowly build their population in the field and affect the crop yield for a long time if not properly managed.

Nematode populations and yield losses are positively correlated to each other. Nematode populations in field conditions are affected by plant genotypes, agro-ecological conditions, several edaphic factors, and local cultural practices. Moreover, nematode population density is also dependent on fertilizer usage, abiotic stress conditions (drought conditions, soil temperature), and distribution of nematodes at any precise location. Management of these nematodes comprises of steps to reduce the nematode population density below the particular species' economic threshold level. In India, the population density of 5 second-stage juveniles (J2s)/gram of soil is considered as economic threshold level for *H. avenae* and *H. fillipjevi* in irrigated wheat (Singh et al. 2009). Several traditional approaches employed to manage nematodes affecting wheat and barley are discussed below.

11.3.1 Cultural Control

Cultural control approaches are recommended for pest management programs as they are sustainable and environmentally friendly. Several agronomic practices indirectly eliminate the resting phases of pests and disease-causing microorganisms (Bernard et al. 2017). An integrated farming system with tailored tillage operations, sowing, organic manuring, judicial fertilization, crop residue incorporation, and restricted pesticide applications resulted in a significant reduction in *H. avenae* population in cereals compared to conventional agricultural practices (El titi and Ibach 1989).

11.3.1.1 Summer Ploughing

In India, soil temperature during summer (May–June) usually remains more than 30 °C and goes up to 48 °C. Deep tillage loosens the soil, thereby disturbing the cysts and exposing them closer to the surface (Mathur et al. 1987). Due to elevated soil temperature, soil moisture evaporates, subjecting the cysts to dry heat. The juveniles and egg stages are sensitive to such desiccation and are killed inside the cysts.

11.3.1.2 Sanitation

Cysts are disseminated by farm equipment, plant products, farm animals, water, or wind. After dissemination, nematodes can take years to become apparent or detectable, leading to additional spreading to new localities. However, phytosanitary quarantine for pests is effective at the country and state levels. Overall, good handling practices and field sanitation must be endorsed for the prevention of dissemination and establishment of nematodes into new localities (Smiley and Nicol 2009).

11.3.1.3 Irrigation

Higher multiplication rates of CCN in well-irrigated wheat and barley, compared to situations with inadequate soil moisture, have been observed (Hugo and Malan 2010). This can be attributed to better plant growth leading to proper root development.

11.3.1.4 Crop Rotation

Cereal cyst nematodes are species-specific, and therefore, their initial population density can be reduced by employing crop rotation with non-host crops such as legumes and oilseed crops (Dababat et al. 2015). Rotating cereal crops with non-host broadleaf crop species or a fallow period for 2 years have been observed to reduce the population density of CCNs on highly infested fields (Andersson 1982; Smiley et al. 1994). However, in intensive cereal cropping systems, this practice is not economical for farmers.

11.3.1.5 Intercropping

The utilization of mustard as an intercrop with wheat has also been observed to diminish the field's prevailing nematode population. Nematodes are adversely affected by glucosinolates from mustard's root exudates (Halbrendt 1996).

11.3.1.6 Manure

The addition of organic amendments such as farmyard manure (FYM), mustard and castor oil cakes, green leaves manures (neem or pungam leaves), sawdust, and composts also negatively affects nematode survival (Thoden et al. 2011). Decomposition leads to the formation of toxic gases inhibiting respiratory and physiological metabolism in nematodes and ultimately killing them (Matthiessen and Kirkegaard

2006). These organic amendments also improve the plant vigor by adding nutrients to the soil and enhancing the population of beneficial microbes and predatory nematodes.

11.3.1.7 Avoidance

Crops can be safeguarded by inducing disruption in the lifecycle of nematodes by altering the time of planting (Ochola et al. 2021). For example, *H. avenae* hatches in low temperatures. Early planted wheat crop can grow deeper root systems before the time of nematode hatching and can be more tolerant to nematode infection. Although this approach is less efficient than crop rotation or genetic resistance, this strategy can be useful in the integrated pest management approach.

11.3.2 Use of Resistant Varieties

The most economical and competent approach for managing CCNs is host-plant resistance. Resistance in PPNs can be characterized as the ability of genotypes to suppress or prevent the nematode reproduction (Trudgill 1991). Natural resistance in wild cultivars/landraces against PPNs can be exploited and introduced in the commercial varieties through marker-assisted or traditional breeding programs. Almost all resistances reported against CCNs in commercial cultivars have been based on introgressions of single dominant genes (Smiley et al. 2017). Resistance to *H. avenae* in barley was first described in 1961 (Andersson 1982). Resistance to *H. avenae* in barley has been mapped to *Rha2* and *Rha4* genes that were identified using RFLP mapping (Kretschmer et al. 1997; Barr et al. 1998). In wheat, six *cre* genes and *Rkn2* have been characterized as R genes against *H. avenae*. Information regarding genes involved in imparting resistance to CCNs is provided in Table 11.2.

Tolerance towards *H. avenae* in barley is usually higher compared to wheat or oats. In India, RajMR-1 cultivar of wheat was recommended for Haryana and Rajasthan states in India to manage *H. avenae* in case of heavy nematode infestation. However, it is very susceptible to yellow rust. Several barley cultivars, namely, Raj kiran, RD2035, RD2052, RD 2508, had shown resistance against cereal cyst nematodes (Bishnoi 2009). Several barley genotypes were screened against three

Table 11.2 Characterized R genes against *Heterodera avenae*

Source	Resistant genes	References
Aegilops variabilis Eig	*Cre2*, *Cre3*, *Cre4*, *Cre5*, *Cre6*, *Cre7* and *Rkn2*	Jahier et al. (2001)
Triticum aestivum L.	*Cre1* and *Cre8*	Slootmaker et al. (1974)
Secale cereale	*CreR*	Asiedu et al. (1990)
Wild relative	*CreX* and *CreY*	Delibes et al. (1993)
Hordeum vulgare L.	*Rha2* and *Rha4*	Kretschmer et al. (1997), Barr et al. (1998)

populations (from Hisar, Jaipur, and Ludhiana) of *H. avenae.* Among the cultivars tested, PL-874, RD-2927 and BH-946 were found to be most suitable for future breeding programs (Koulagi et al. 2018). There is a need to explore the resistant cultivars against the specific population of nematodes due to different pathotypes. When pathotypes are considered, the exploitation and transfer of genes conferring horizontal resistance is necessitated compared to vertical resistance which is species-specific in nature (Trudgill 1986).

11.3.3 Utilization of Biocontrol Agents

In an agro-ecosystem, biocontrol agents exhibit multiple strategies against their target host, including parasitism, toxin secretion, leading to induced systemic resistance and plant growth promotion (Dong and Zhang 2006). The nematode densities in the fields can be manipulated by the uses of various fungi like trapping fungi, egg parasitic fungi, opportunistic fungi, endophytes, and fungi secreting nematotoxic chemicals. Fungal biocontrol agents such as *Trichoderma harzianum*, *T. viride*, *Purpureocillium lilacinum*, *Pochonia chlamydosporia*, and *Nematophthora gynophila* have been recorded to act against CCNs (Kerry 1990). Several bacteria have been observed either as parasitizing agents (*Pasteuria nishizawae*) or affect nematodes by producing toxins (*Bacillus* and *Pseudomonas* spp.) (Abd-Elgawad 2016). Alternatively, the application of plant growth promoting rhizobacteria (PGPR) and vesicular-arbuscular mycorrhiza (VAM) can safeguard the crops against damages by nematodes by enhancing plant vigor and induction of several inhibitory metabolites (Ingham 1988; Mhatre 2019).

11.3.4 Application of Chemical Nematicides

Chemical nematicides are employed when other cultural or biocontrol approaches are inadequate and do not result in effective management of nematodes. The rational uses of nematicide as seed dresser, seed soaking, bare-root dip treatment, and nursery bed treatment are effective against managing PPNs (Chitwood 2003). Majority of earlier nematicides are now banned due to their harmful effects on aquatic and terrestrial ecosystems and other health-related issues. Recently two new nematicides, namely, Fluensulfone 2% Gr marketed as Nimitz (Adama Ltd.) and Fluopyrum 34.48% SC marketed as Velum prime (Bayer crop sci.), have been registered in India and their efficacy trials are under progress in various crops. Initial trials suggest that these nematicides work well against CCNs. Once studied thoroughly for their efficacy against cereal cyst nematodes, it can be recommended for field use or seed treatments (Ebone et al. 2019).

11.4 Modern Approaches for Nematode Management in Wheat and Barley

Limitations of conventional breeding for nematode resistance include extensive screening of candidate genotypes for identification of suitable parents and considerable time required to incorporate the resistance as well as absence of well-defined resistance traits in the target host species. Nowadays, utilizing Marker Assisted Selection (MAS) for pyramiding resistance imparting genes is helping in expediting resistance breeding. An alternative strategy is to engineer transgenic plants that provide resistance to nematodes by transferring functional resistance genes or "synthetic" resistance genes that cause perturbation in nematode-plant interaction. Some of these new approaches are discussed below.

11.4.1 RNA Interference

The discovery of RNA interference (RNAi) provided a revolutionary approach to study gene function. RNAi, a highly conserved fundamental biological process, was first discovered in the model animal *Caenorhabditis elegans* which is a free-living nematode (Fire et al. 1998). RNAi achieves sequence-specific targeted gene silencing through post-transcriptional silencing. A double-stranded RNA (dsRNA) homologous to a target sequence is recognized in the cell and through a series of steps leading to deterioration of the dsRNA as well as the targeted homologous mRNA. RNAi as a tool is useful because of its specificity as well as its ability to cause silencing away from the site of dsRNA introduction in the tissue (Tomoyasu et al. 2008; Whangbo and Hunter 2008). The PPNs ingest macromolecules while feeding on the cytoplasm of the plants and the small size of dsRNA allows its ingestion through nematode stylet (Banerjee et al. 2017). Uptake of dsRNA has been visualized in nematodes through fluoroscein isothiocyanate (FITC) marker in multiple studies (Urwin et al. 2002; Rosso et al. 2005; Dutta et al. 2015). Thus, RNAi in the form of host-delivered dsRNA is a powerful tool against PPNs for silencing key genes.

In vitro RNAi is an approach popularly used to functionally characterize important parasitic genes of PPNs. The first demonstration of in vitro RNAi in PPNs was done using a neuroactive compound octopamine to facilitate dsRNA uptake by J2s of cyst nematodes, *G. palida* and *H. glycines* (Urwin et al. 2002). Due to PPN's obligatory parasitic nature, eggs and J2s of the sedentary PPN species are utilized to perform in vitro RNAi through a soaking method of delivery (Lilley et al. 2012). Several phenotypic changes due to in vitro RNAi (e.g., reduced pathogenicity, decreased fecundity, reduced motility, decrease in host recognition, and perturbed penetration and reproduction) are associated with downregulation of the targeted nematode genes (Lilley et al. 2012; Cheng et al. 2013; Tan et al. 2013; Dash et al. 2017). Relatively few studies on functional characterization of CCN genes through in vitro RNAi are available as compared to other PPNs. This can be attributed to difficulty in handling and culturing along with limited availability of transcriptomic

Table 11.3 Studies related to gene silencing against cereal cyst nematodes

Nematode species	Target gene	Approach	Phenotype observed	Reference
Heterodera avenae	Nuclear hormone receptor gene, polyadenylate binding protein gene, intron binding protein gene, and *epsin* gene	dsRNA soaking	Reduced number of females and eggs in all except nuclear hormone receptor where an 25% increment was observed	Gantasala et al. (2015)
H. avenae	FMRF like neuropeptide (*FLP-4*)	siRNA soaking	40% reduction in nematode survival	Zheng et al. (2015)
H. avenae	Expansin like protein (*HaEXPB2*)	dsRNA soaking	53% reduction of nematodes in roots	Liu et al. (2016)
H. avenae	Neuropeptides: *nlp15, flp18 GPCR, flp2, flp12, flp16*	dsRNA soaking	Reduction in nematode penetration and reproduction in wheat	Dutta et al. (2020)
H. avenae	Protease inhibitors and proteases: *Serpin, sp, sp1, cpz, cps, cpb, cpl*	dsRNA soaking		
H. avenae	Secretory proteins: *hsp12, cm, crt, vap-1, RanBPM, 4D06, ds12*	dsRNA soaking		
H. avenae	Cell wall-modifying enzymes: *galectin, glycosidase, GH38, GH32, GH30, exp, cht, cbn, cht1, pel*	dsRNA soaking		
H. avenae	Housekeeping genes: *acad, tp, zmp, gtf, apc, gpcpd*	dsRNA soaking		
H. avenae	Stress response: *HSP1, HSP75, HSP90, LRR*	dsRNA soaking		
H. avenae	Reproductive fitness: *msp20*	dsRNA soaking		
H. avenae	Chemosensory response: *gcy*	dsRNA soaking		
H. avenae	*serpin*, *cathepsin* L, *flp12*, *RanBPM, galectin, vap1* and *chitinase*	HIGS	Reduction in nematode penetration and reproduction in wheat	Dutta et al. (2020)

information. In vitro RNAi has been performed in *H. avenae* in various previous studies (Table 11.3) and phenotypes pertaining to reduction in nematode pathogenicity and development have been observed.

In recent years, nematode genomics have come a long way after genome sequencing of RKN *M. incognita* (Abad et al. 2008). These genomic and transcriptomic resources have emerged as a quintessential tool to mine gene targets for managing PPNs. The genome of *H. avenae* has not been sequenced yet. However, transcriptome of J2s and adult stage of *H. avenae* can be accessed through HATdb (http://insilico.iari.res.in) which is a convenient genetic resource for functional analysis of *H. avenae* genes (Kumar et al. 2014). Study of *H. avenae* genes via an in vitro RNAi screen for functional validation can identify key genes to develop transgenic CCN resistant plants by employing host-induced gene silencing (HIGS) strategies.

Host plants are genetically engineered to express dsRNA of the targeted gene to achieve *in planta* (host-delivered) RNAi. An RNAi construct for any target nematode gene is developed by cloning a fragment of the target gene coding sequence in sense and antisense orientation. The cloned fragment is separated by an intron or spacer region along with a strong promoter (constitutive or tissue specific) that drive the expression of dsRNA. After transcription, a hairpin structure (which is mostly dsRNA) is formed after complementation of sense and antisense strand of the target gene after splicing of introns (Smith et al. 2000; Helliwell and Waterhouse 2003). The transcribed dsRNAs are either directly ingested or spliced in to siRNAs via plant dicer to be subsequently ingested by targeted nematodes (Bakhetia et al. 2005; Dutta et al. 2015). Host-induced gene silencing (HIGS) is arduous to attain in case of wheat and barley against CCNs. A recent study employed HIGS to target *cathepsin L*, *chitinase, galectin*, *flp12, RanBPM, serpin*, and *vap1* gene of *H. avenae* in wheat resulting in 33.24–72.4% reduction in the nematode multiplication (Dutta et al. 2020). The cysts formed on these transgenic plants showed developmental retardation in the form of smaller size along with translucent cuticle. This study demonstrates that HIGS can be employed to manage CCNs in wheat and barley in future. Biostimulants from metabolites of soil streptomycetes have also been seen to affect *H. avenae* by inducing RNAi in wheat in a non-transgenic approach by inducing plant si/miRNA complementary to nematode genes (Blyuss et al. 2019). Another non-transgenic approach to employ RNAi-based management is by using topical RNAi.

11.4.2 Proteinase Inhibitors

In addition to RNAi, another molecular approach against CCNs is utilization of protease inhibitors (PIs) against nematodes as antifeedants. A few proteinase inhibitors like cystatins, cowpea trypsin inhibitor (CpTI), and serine-based PIs have been utilized against nematodes. PIN2; a type of serine protease inhibitor from *Solanum tuberosum* was found effective in inducing resistance against *H. avenae* in *Triticum durum* (Vishnudasan et al. 2005). This protease inhibitor does not impart bio-safety issues for humans as cystatin is part of human diet and is a non-allergen. Also, these studied PIs are found to be digested by gastric juices. Proteinase inhibitors have been studied many different crops (Lilley et al. 1999; Ali et al. 2017). Further studies are warranted in this area to investigate various classes of PIs and their effective utilization in PPN management.

11.4.3 Chemosensory Disruptive Peptides

PPNs utilize chemical cues present in root exudates in soil to reach host for penetration. To hinder root invasion by PPNs, non-lethal synthetic peptides have been utilized as an anti-root-invasion approach. These peptides disrupt the chemosensory ability of the nematodes and adversely affect nematode chemotaxis towards host roots. This approach has been studied against *G. Pallida* (52% reduction of females on potato roots) and *H. schactii* (Liu et al. 2005; Wang et al. 2011). These reports are evidence that chemoreceptive nematode repellent peptides can also be used to induce resistance in wheat and barley against CCNs.

11.4.4 Future Technologies

Nowadays, genome editing is being utilized for developing genotypes having traits for resistance against pests and diseases (Yin and Qiu 2019). The genome editing technologies include zinc finger nucleases (ZFNs), transcription activator like effector nucleases (TALENS) and the clustered regularly interspaced short palindromic repeats (CRISPR)-Cas system. Genome editing is yet to be demonstrated as an approach for management of any plant parasitic nematode. However, several phylum-wide comparative genomics and transcriptomics studies have identified important genes and metabolic choke-points for parasitic nematodes. These key host genes facilitating nematode development and parasitism can be targeted using the modern approaches of host-delivered RNAi, HIGS, and genome editing techniques to provide defense against various nematode-parasites attacking cereals.

11.5 Conclusions and Future Prospects

Increasing human population puts a huge pressure on the scientific community to find ways to improve yields of cereal crops and including wheat and barley in the future. The overall production of wheat and barley has so far increased due to introduction of improved varieties and technologies, better management of cropping systems, etc. However, the biotic and abiotic factors including nematodes always pose a tough challenge. Wheat and barley crops are infested by various PPNs and the cereal cyst nematodes are one of the major challenges for these crops. A number of management options have been exploited to control cereal cyst nematodes which are nature and condition specific (Table 11.4). A single method cannot achieve the total eradication of these nematodes; therefore, integration of several methods can help in reducing the population level of nematodes below threshold level. Traditionally integration of cultural, biocontrol, and chemical management methods is used for managing CCNs. Nimitz and Velum Prime nematicides are being evaluated for CCNs, but more nematicides are required. In recent times, molecular approaches are gaining popularity as these are rapid and cost-effective tactics of pest management. The discovery of resistance genes by genotyping by sequencing or whole

Table 11.4 A summary of nematode management strategies employable in wheat and barley cropping systems

Objective	Strategy	Tool
Exclusion—avoidance	National and domestic quarantine	Avoidance of nematode invasion in to new locality
Reduce initial population density	Physical control	Tillage, including residual root destruction
	Cultural control	Timing of planting
		Inter- and intra-cropping
		Trap crops
		Soil amendments
		Crop rotation
		Farm sanitation
		Weeding
	Biological control	Addition of nematode antagonistic fungi, parasitic bacteria, PGPR, VAM
Suppress nematode reproduction	Resistance and tolerance	Cultivation of resistant and tolerant varieties
	Transgenic plants	Host-induced gene silencing of targeted nematode gene
		Proteinase inhibitors
		Antifeedant peptides
Restrict current crop damage	Tolerance	Nematode tolerant cultivars
	Nematicide application	Manage the current nematode population density

genome sequencing is an important strategy to identify, isolate, and use these genes in commercial cultivars. The transcriptomic analysis of wheat and barley can lead to identification and downregulation of nematode's genes involved in invasion and development of syncytium. As stated above, several phylum-wide comparative genomics and transcriptomics studies have identified important nematode genes and metabolic choke-points. The key host genes facilitating nematode development and parasitism can be targeted using modern approaches of host-delivered RNAi, HIGS, and genome editing techniques to provide defense against various nematode-parasites attacking cereals. Lastly, researchers are working on ectopic delivery of dsRNA (spray formulations) as a part of development of modern and non-transgenic approaches against nematode-pest management, which will be used for the management of cereal nematodes in future.

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Nanotechnology for Wheat and Barley Health Management: Current Scenario and Future Prospectus

12

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12.1 Introduction

Wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) are among the most indispensable cereal crops and large portions of human populations in different corners of the world relied on them as a potential source of food and animal feed. Both crops have the potential to grow in a wide range of agro-climatic environments, however, wheat and barley are adversely affected by global climate changes and therefore raising concerns regarding future food security. Different forms of environmental stresses such as drought, salinity, high temperature, and low light intensity badly influence the growth and grain yield of wheat and barley, and, thus resulting in low yields (Modarresi et al. 2010; Akter and Islam 2017; Sallam et al. 2019; Kharub et al. 2017). Besides abiotic stresses, both the crops are attacked by different types of pathogens and insect pests which causes considerable loss to grain yield and quality (Kashyap et al. 2020a, 2021; Kumar et al. 2020; Kamran et al. 2013; Jasrotia et al. 2019). At present, wheat and barley diseases are managed by adopting integrated disease management modules based on technologies available (Singh et al. 2020). These approaches are constrained by the complexity of stress tolerance attributes, as well as poor genetic variability of yield components under stress conditions and dearth of precise and proficient selection standards. Other demerits include their operation easiness, economics and technical skills. Under such circumstances, there is always a requirement of practical, inexpensive and

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practicable strategies that can overcome these limitations. Under such circumstances, it becomes utmost important to search and explore novel alternatives like nanotechnology for their utilization to supplement current stress management approaches. Nanotechnology is acknowledged as one of incipient science of twenty-first century, creating a remarkable influence on the global commerce, industry, and human livelihoods by introducing nanoparticles, quantum dots, nanorods, nanocarriers, nanotubes, nanodrugs, and nanosensors etc. (Worrall et al. 2018; Kashyap et al. 2020a). Nanoparticles have size dependent features, high surface-to-volume ratio and exceptional optical characteristics that provide extra-ordinary physio-chemical and biological characteristics (Kashyap et al. 2015). Jasrotia et al. (2018) reviewed the scope and role of nanotechnology for wheat production and highlighted the prospective application of nanotechnology in developing novel nanoproducts such as nanofertilizer, nanopesticide, nanoherbicide, nanosensor and new generation delivery systems for sustained and targeted release of agrochemicals. Kashyap et al. (2019a) also highlighted the potential of nanotechnology in wheat production and protection under changing climate scenario. Therefore, in current chapter, comprehensive account on the effect of nanoproduct application on the wheat and barley crops (Table 12.1) along with the research breaches in the field of application of nanoparticles and way forward to introduce an eco-compatible application of nanoparticles for the alleviation of biotic and abiotic stress in these crops have been presented.

12.2 Biotic Stress Problems in Wheat and Barley

Biotic stresses imposed by pathogens and insect pests are a prime threat to profitable and healthy cultivation of wheat and barley throughout the world. Predominately, the yield and grain quality of both the crops are negatively influenced by diseases of fungal nature. Among various diseases, rusts (yellow, black and brown), foliar blights, Karnal bunt, powdery mildew and loose smut are of major economic significance in wheat (Kashyap et al. 2011. 2019a, 2020b; Singh 2017). Other region specific diseases include flag smut, foot rot, head scab, hill bunt, blast, viral and bacterial diseases. Previous studies reported that diseases cause 15–20% loss of wheat yield per year, but losses may reach beyond 50% when the flag leaf suffers from severe disease in heading and grain filling stages (Figueroa et al. 2018; Griffey et al. 1993). Singh et al. (2005) reported that leaf and stripe rust caused approximately 63% and 46% yield reduction in major wheat growing regions of South Asia respectively, if susceptible varieties are cultivated. According to Park (2007), leaf rust alone has the potential to decline grain yield by 60%, while stem rust could result in100% yield reduction under congenial environment for disease outbreak. It is predicted that global annual monetary losses due to wheat rust diseases ranged between US$ 4.3 to 5.0 billion (Figueroa et al. 2018). In case of yellow rust, global monetary losses of nearly US$ 1 billion annually has been reported (Beddow et al. 2015; Wellings 2011). Murray and Brennan (2009) recorded AU$ 127, AU$ 12 and AU$ 20 million loss per year due stripe rust, leaf rust and Septoria tritici blotch

Table 12.1 Nanotechnology mediated interventions in amelioration of abiotic stresses in wheat and barley

Type of stress	Crop	NPs/ formulation	Concentration/ dosage	Type of assay	Research outcome	References
Drought	Wheat	Ag NPs	10 mg L^{-1}	Pot	Induce drought resistance and improve yield	Ahmed et al. (2021)
	Wheat	Cu NPs	3 mg L^{-1}	Pot	Induce drought resistance and improve yield	Ahmed et al. (2021)
	Wheat	SeNPs	30 mg L^{-1}	Pot	Increase in plant height, shoot length, shoot fresh weight, shoot dry weight, root length, root fresh weight, root dry weight, leaf area, leaf number, and leaf length	Ikram et al. (2020)
	Wheat	Fe-NPs	100 mg kg^{-1} soil	Pot	Improve in the photosynthesis process, yield, Fe concentrations and diminished the cd concentrations in tissues under drought stress	Adrees et al. (2020)
	Wheat	TiO_2 NPs	500–2000 mg L^{-1}	Petri dish	Promote seed germination and early growth of wheat under drought stress	Faraji and Sepehri (2019)
	Wheat	TiO_2 NPs	2000 mg L^{-1}	Pot	Improved the growth, antioxidant system, and photosynthetic performance of wheat seedlings under drought stress	Faraji and Sepehri (2020)
	Wheat	ZnO-NPs	2.17 mg kg^{-1}	Pot	Promotes wheat performance and enhances Zn uptake under drought stress	Dimkpa et al. (2020)
	Barley	Si NPs	125 mg L^{-1}	Pot	Post-drought recovery of barley plants via modifying plant morpho-physiological and antioxidative attributes and synthesis of specific metabolites	Ghorbanpour et al. (2020)
	Barley	Si NPs	20 ppm	Field	Significant increase in plant height, seed weight, biological yields and economic seed yield under water stress conditions	Ghorbanian et al. (2017)
	Barley	Chitosan NPs	60–90 ppm	Pot	Significant increase in relative water content (RWC), 1000-grain weight, grain protein, proline content, CAT SOD compared to the control udner drought conditions	Behboudi et al. (2018)
Salinity	Wheat	Fe_3O_4 NP	0.5 ppm	Field	Alleviate the effects of salt stress by activating growth, chlorophyll content, SOD, glutathione, and soluble proteins	El-Saber et al. (2021)

(continued)

Table 12.1 (continued)

Type of stress	Crop	NPs/ formulation	Concentration/ dosage	Type of assay	Research outcome	References
	Wheat	ZnO NPs (21–41 nm)	0.25 ppm	Field	Enhanced tolerance to salinity stress; increase in pigment and GSH content and decline in MDA content	Farroh et al. (2020)
	Wheat	CuO NPs	1 ppm	Field	Better viability for wheat genotypes under saline stress by increasing growth characteristics, total pigments, and antioxidant enzymes activities	Mahdi et al. (2020)
	Barley	Se NPs	100 ppm	Pot	Promote the growth of barley seedlings under salt stress and reduction of MDA content	Habibi and Aleyasin (2020)
Heat	Wheat	Ag NPs	50 and 75 mg L^{-1}	Pot	Improvement in morphological growth of wheat plants under heat stress	Iqbal et al. (2019)
	Wheat	Zn NPs	10 ppm	Field	Enchantment in antioxidant enzymes activities and reduction in lipid peroxidation product malondialdehyde	Hassan et al. (2018)
	Wheat	Fe NPs	0.5 ppm	Field	Enhancement in antioxidant enzymes activities (and reduction in lipid peroxidation product malondialdehyde	Hassan et al. (2018)
	Wheat	Fe_3O_4 NPs	0.25 ppm	Field	Enhancement in wheat yield and quality	Borai et al. (2017)
Heavy metal	Wheat	Fe_3O_4 NPs	2000 mg L^{-1}	Petri dish	Activate protective mechanisms to reduce oxidative stress induced by metals (Pb, Zn, cd and cu) in the wheat seedlings	Konate et al. (2017)
	Wheat	Fe-NPs	100 mg kg^{-1}	Pot	Improved the photosynthesis, yield, Fe concentrations and diminished the cd concentrations in tissues	Adrees et al. (2020)
	Wheat	ZnO NP	100 mg kg^{-1}	Pot	Promote wheat productivity and effectively alleviate soil cd contamination	Khan et al. (2019)
	Wheat	ZnO NPs	100 mg L^{-1}	Pot	Increase in plant biomass, nutrients and decrease in cd toxicity	Rizwan et al. (2019)
	Wheat	Fe NPs	20 mg kg^{-1}	Pot	Increase in plant biomass, nutrients and decrease in cd toxicity	Rizwan et al. (2019)

disease, respectively in Australia. Similarly, foliar leaf blights results in 20% grain yield loss in India (Joshi et al. 2004), however, it may be reached up to 80% under heavy infection (Joshi et al. 2007). Moreover, 10–20% potential yield losses due to heavy infestation of leaf blight disease in wheat have been recorded in Brazil, Paraguay, and Argentina (Annone 1997). In the USA, yield losses due to *Fusarium* head blight have been reported in the tune of US$ 3 billion financial loss between 1990 and 2008 (Schumann and D'Arcy 2006). Similarly, 40–100% yield losses have been observed in case of wheat blast disease (Igarashi 1990; Kumar et al. 2021). The estimates reported by Bockus et al. (2001) revealed 1.88% and 1.6% yield loss due to *wheat streak mosaic virus* (*WSMV*) and *Septoria* complex in wheat. Further, they also reported that outbreaks of barley yellow dwarf virus (BYDV) or tan spot assessed independently cause less than 3% annual yield losses, and in general not more than 0.1–2% yield loss occur due to these diseases (Bockus et al. 2001). *Tilletia indica*, a quarantine pathogen of wheat, reported to cause 0.01–1% annual yield loss, although ex-ante analysis revealed that wheat market in Australia would suffered with a financial loss of 490,900,000 Australian dollars per annum, if *T. indica* fungus reached inside the country (Bishnoi et al. 2020). Besides this, flag smut diseases reported to cause 20% crop loss in Egypt, Iran, Italy and USA (Purdy 1965; Kumar et al. 2019). Moreover, in India and China, yield loss of 5% and 90–94% due to this disease has been documented (Yu and Hwang 1936; Padwick 1948; Kashyap et al. 2020a). Similarly, another smut fungus reported to cause 5–20% annual yield losses at 1–2% an infection of *Ustilago segetum tritici* infection in wheat (Wilcoxson 1996; Kashyap et al. 2019a). Like wheat, barley also attacked by diverse types of biotic stresses and among them, diseases are reported to cause significant reduction in yield and grain quality. Mathre (1997) catalogued 80 different diseases caused by infectious agents in 'Compendium of Barley Diseases', however, yellow and brown rusts, covered smut, powdery mildew, net-blotch, spot blotch, speckled leaf blotch, stripe, yellow dwarf and molya disease are acknowledged as economically important diseases (Gangwar et al. 2018). Cotterill et al. (1994) recorded 31% yield losses due to barley leaf rust (*Puccinia hordei*) diseases in Australia. Griffey et al. (1994) reported complete destruction of barley nurseries when *P. hordei* fungus reached at epidemic threshold level before heading stage followed by 58% yield loss due to same disease in barley (van Niekerk et al. 2001). In India, the yield losses due to stripe and net blotch diseases documented to the tune of 20–70% and 20–30%, respectively (Kumar et al. 1998). Under moderate to high disease pressure, *Drechslera teres* fungus inciting spot-type symptoms on barley reported to reduce grain yield by 19–32%, respectively (Jayasena et al. 2002; Khan 1989) and also cause reduction in grain size, which is one of the vital malting barley grain quality criterion. Yield reduction by 23–44% in barley due to spot-type net blotch diseases has been reported by Jayasena et al. (2007). Further, they also reported that with every 10% rise in disease intensity on the top three leaves of barley crop, there is a possibility of 0.4 t ha^{-1} yield loss. Recently, Jalli et al. (2020) analyzed the data from 449 field trials of wheat and barley crops and concluded that >50% leaf blotch disease severity at Zadoks growth stage 73–77, resulted in the average yield loss of 1072 kg ha^{-1} and 1114 kg ha^{-1} in in winter wheat and spring barley, respectively.

Generally, insect pests cause damage in terms of yield and quality in crops but identified as minor threats in case of wheat and barley crops. Earlier published literature indicated that global yield losses due to insect pests rise from 5.1% to 9.3% from pre to post-green revolution era (Jasrotia et al. 2021). Usually, sucking and feeding insects are not directly responsible for major damage in wheat and barley until their population attained critical threshold level. Incursion by aphids (*Sitobion avenae* or *Rhopalosiphum padi*) feeding on wheat showed higher *BYDV* incidence (Kamran et al. 2013). In some locations, Russian wheat aphids (*Diuraphis noxia*) and greenbug (*Shizaphis graminum*) cause injury by releasing a toxin inside invaded plant foliage. The cumulative direct and indirect losses economic loss of $893 million due to Russian wheat aphid (*Diuraphis noxia*) has been recorded by Morrison and Peairs (1998). Similarly, Butts et al. (1997) also observed 37% yield losses in winter wheat due to this pest.

12.3 Abiotic Stress Problems in Wheat and Barley

Abiotic stresses significantly hampered productivity of wheat and barley and causing to considerable yield losses. According to global analysis, different abiotic stresses are responsible for causing approximately 50% yield loss in principle agricultural crops. There are several evidences which indicated 2 °C rise in global temperature in coming five decades (Wrigley 2006; You et al. 2009). A meta-analysis study conducted by Challinor et al. (2014) indicated a significant yield loss in wheat in temperate and tropical terrains with every 2 °C increase in temperature. This observation was also supported by the findings of climate modeling research that reported 6% decline in wheat production (Asseng et al. 2015). It is worth mention here that 1 °C rise in temperature in wheat growing season could lessen the wheat yield by 3–10% (You et al. 2009). Similarly, Mohammadi (2002) noticed an average yield loss of 1.7% per day, when optimum period for wheat sowing is not followed. Besides temperature, soil salinity and sodicity also reported as potential abiotic constrains in successful and profitable cultivation of wheat and barley. It has predicted that approximately 830 million hectares i.e. >6% of the world's land is suffered from salinity and sodicity (Genc et al. 2019). Jamil et al. (2011) highlighted that in the aberrance of proper and sustainable control of salinity stress, 50% of the highly productive agricultural land of the world will be salinized by 2050. Moreover, wheat yield reductions of 88%, 50% and 70% under high irrigation salinity, dry land salinity and sodicity, respectively have been observed (James et al. 2012; Rengasamy 2002; Jafari-Shabestari et al. 1995). Moreover, water paucity due to global climate change is accompanied by regular and more severe summer droughts. Water is an essential element for plant existence and play mandatory role in the transport of nutrients, therefore water scarcity triggers drought stress, which ultimately lead to poor wheat and barley crop stands (Qadir et al. 1999; Zhao et al. 2009; Wang et al. 2015; Sallam et al. 2019). Drought obstructs wheat development at all the critical growth stages and results in extensive yield losses during the flowering and grain-filling stage (Araus et al. 2003; Jasrotia et al. 2018). In this regard, Zhang et al. (2018) estimated that post-anthesis drought stress can decline total wheat yield by 1–30%, while cause more grain yield loses (8–92%) under prolonged drought stress events at flowering and grain filling stage. Besides drought, wheat is very receptive to heat stress and adversely impacted the phenotypic development of wheat by altering photosynthetic machinery (Abdelrahman et al. 2020; Akter and Islam 2017). Heat stress is defined as the rise in temperature beyond a threshold level for a sufficient period of time to cause irretrievable growth and development changes in plant. Mondal et al. (2013) documented the multifaceted impact of heat stress on plants that badly hampered the physiological growth and development. Broadly, heat stress causes lipid peroxidation due to abrupt oxidative stress, leading to the rapid damage of thylakoid membranes and disruption of their function, which finally reduced photosynthesis and crop yield (Abdelrahman et al. 2020). It has been reported that short period (2–5 days) exposure at reproductive stage wheat to heat stress (>24 °C) cause significant damage to the fertility of florets, while average daily temperature of 35 °C resulted in complete crop failure (Prasad and Djanaguiraman 2014; Sehgal et al. 2018). Balla et al. (2011) also reported 31 and 57% yield losses in wheat due to heat stress and drought respectively. In India, 11.6 to 43.6% wheat yield losses due to moisture stress have been observed under no irrigation application during the entire crop season (Tiwari et al. 2015). Research also indicated that water logging negatively influence the wheat kernel and tiller numbers. It has been reported that 20 days waterlogged spell at 3–4 leaf stage results in significant reduction of dry mass (95%) and yield (90%) relative to control in case of wheat (Collaku and Harrison 2002; Ploschuk et al. 2018). On the other hand barley plants attained 85 and 90% gain in dry mass and yield respectively, when compared with control (Masoni et al. 2016). Further, it was noticed that in case of barley, waterlogging negatively affects the chlorophyll, protein, and results in the repid degradation of RNA. Besides this, reduction in the concentration of nutrients like nitrogen, phosphorus, metal ions, and minerals in shoot has been observed due to waterlogged conditions in barley (Ciancio et al. 2021; Wei et al. 2019). Statistically, 39–40% loss in potential yield have been noticed (Collaku and Harrison 2002; Musgrave and Ding 1998), however, it may be reach up to 50% under severe water logging regimes (Setter and Waters 2003). Waterlogging is reported to lessen barley grain yield by 30–60% (de San Celedonio et al. 2014; Xiao et al. 2007).

12.4 Nanoparticle Synthesis and their Influence on Plant Growth and Development

Synthesis of different kinds of nanoparticles has bloomed as a fascinating research sector from past several decades. Different types of biological sources such as fungi, bacteria, virus, yeast, actinomycetes and botanicals have been explored as ecofriendly factories for the fabrication of nanoparticles (NPs) (Jadoun et al. 2021; Gautam and Avasthi 2020; Kashyap et al. 2018; Ovais et al. 2018). All these biological resources display high efficiency as reducing and stabilizing means for the production of novel nano-materials for agriculture and industrial applications

(Kashyap et al. 2015, 2018). There are two main methods of NP production i.e. top down and bottom up methods (Kashyap et al. 2013). In top down approach, nanoparticles are synthesized through various kinds of synthesis procedures such as ball milling, lithographic techniques, etching, and sputtering etc. On the other hand, in bottom up method, nanoparticles are synthesized from simpler molecules and involve myriads of strategies such as sol-gel processes, chemical vapor deposition, atomic condensation, spray pyrolysis and laser pyrolysis etc. Application of these methods in the production of different types of nanoparticles using metal and metal oxide [e.g., silver (Ag), gold (Au), zinc oxide (ZnO), copper oxide (CuO), silicon dioxide, titanium oxide, iron oxide, aluminum oxide, magnetite and cerium oxide etc.] been reported and research progress in this area have been reviewed by several workers (Ijaz et al. 2020; Singh et al. 2018; Duan et al. 2015; Thakkar et al. 2010).

A large number of evidences indicated that different types of nanoparticles have both negative and positive impact on the growth and development of plants when used in different concentrations (Kashyap et al. 2020a). For instance, significant gain in wheat growth (9.0%), shoot biomass (12.7%), and grain yield (36.6%) have been observed by using cerium oxide ($nCeO_2$) nanoparticles (Rico et al. 2014). Hu and Zhou (2014) highlighted the application of biocompatible hydrated graphene ribbon in enhancing germination rate of aged wheat seed and their oxidative stress tolerance capabilities. Larue et al. (2012) observed no influence of TiO_2NPs on seed germination in wheat. However, they observed that synthesized NPs can move through roots to the leaves and further noticed that the <36 nm size NP matters for NPs translocation as accumulation of <140 nm TiO2NPs observed only in wheat root. Riahi et al. (2012) found that nAl_2O_3 (<50 nm) application on wheat leaves results in the reduction of root length due to oxidative stress imposed by rise in activities of catalase and superoxide dismutase (SOD). In another study, Schwabe et al. (2013) studied the effects of CeO_2 NPs exposure on wheat by using hydroponic system and reported only minute growth reduction or low toxic effect on wheat seedlings, however, enhanced activities of catalase and ascorbate peroxidise enzymes were noticed. Mahmoodzade and Aghili (2014) reported significant rise in root and shoot growth in response to nano titanium dioxide (1200 ppm) treatment in wheat. In another research, Ramesh et al. (2014) revealed positive beneficial impact of ZnO on seed germination of wheat in concentration dependent manner. Similar results were published by Hafeez et al. (2015) in case of Cu-NPs, where Cu-NPs (0.8 ppm) do not show any negative affect on the seed germination of wheat, however, impaired wheat seed germination when plants treatment with 1 ppm or more concentration of Cu-NPs. The effect of the biosynthesized AgNPs (100 mg L^{-1}) on wheat growth was investigated by Farghaly and Nafady (2015). They noticed non-significant inhibitory impact of AgNPs on seed germination rate, dry weight and pigment fractions. Yasmeen et al. (2017) reported significant improvements in spike length, number of grains per spike, and grain weight in response to seed priming of wheat plants with Fe NPs and Cu NPs. Joshi et al. (2018) noticed that wheat seeds primed with multi-walled carbon nanotubes (90 μg mL^{-1}) showed significant increase in spike length (21%), spike weight (27%), number of spikelets (20%), and grain production (32%). Similarly, positive impact noticed in CuO NPs (0.1 and 0.01 gm L^{-1}) primed wheat seeds in the early stages of plant growth. However, residual impact of CuO NPs (0.10 and 1.00 gm L^{-1}) was also detected (Zakharova et al. 2019). In another study, Wang et al. (2019) noticed increase in the growth, development and amino acid contents (tyrosine and cysteine) in Fe -NPs (50 and 500 mg kg^{-1}) treated wheat plants. Al-Amri et al. (2020) observed enhanced root length, plant height, biomass, and chlorophyll content of wheat in response Fe_2O_3 NMs (20–40 nm) application and further concluded that these NMs can move in the wheat plant and translocate to the leaves which could be possible reason behind the growth enhancement. However, confocal microscopy study reports the toxicity of Fe_2O_3 NMs in root-tip cells reflecting any visible toxic symptom and therefore the movement of NMs inside wheat plant warrant further research explorations on their impacts on the end users.

In case of barley, Vecerova et al. (2016) observed stimulatory impact of CdO NPs on total amino acids content and sugars without any major adverse effect on total secondary metabolites production but altered saturate and unsaturated fatty acid contents in the roots and leaves have been noticed. Similarly, positive results of manganese ferrite nanoparticles (1000 mg L^{-1}) on growth have been published by Tombuloglu et al. (2018). They noticed the movement of nFe_2O_4 NPs from roots to leaves and correlated nFe_2O_4 NPs with the growth promotion of barley. Tombuloglu et al. (2019) also found positive influence of the calcium and magnesium substituted strontium nano-hexaferrite (500 mg L^{-1}) on mineral uptake, magnetic character, and physiology of barley. Evidence of phytotoxicity and genotoxicity of CeO_2 and TiO_2 in barley has been reported by Mattiello et al. (2015). Further, they also highlighted the probable reason such as particle size, NPs concentration in a suspension, direct adsorption of NPs onto the root structures and their ability to dissolve metal ion in the medium-root interface zone for the toxicity of CeO_2 and TiO_2 (500 mg L^{-1}) in barley seedlings. Similarly, negative effect of nanoparticles has been noticed, when hematite (α-Fe_2O_3) NPs (400 mg L^{-1}) applied at germination and seedling stage of barley in hydroponic culture (Tombuloglu et al. (2020). Results clearly show significant reduction in germination rate, chlorophyll and carotenoid contents of barley plants due to cell membranes injury caused by NPs in root zone. In another study, Plaksenkova et al. (2020) demonstrate that zinc oxide NPs (4 mg L^{-1}) increase seed germination, shoot and root elongation and H_2O_2 stress level, however reduction in the root cell viability and genomic template stability in barley seedlings has also been noticed. Recently, Petrova et al. (2021) examine the impact of Fe_3O_4 and CuO NPs on *mlo*-resistance-related miRNA expression, genotoxicity, and seedling morphology in different barley cultivars in concentration dependent manner (17, 35, and 70 mg L^{-1}). Interestingly, Fe_3O_4 and CuO NPs reflected contrasting results on two different barley varieties. For instance, Fe_3O_4 NPs showed increase in plant shoot, root lengths and fresh biomass, but not occurred in case of CuO NPs. Moreover, it was also noticed that CuO NPs caused major alterations in barley genome compared to Fe_3O_4 NPs. Therefore, from aforementioned studied, it is clearly evident that NPs has concentration dependent positive and negative impact on wheat and barley crops and therefore it becomes utmost important to explore environmental diffusion of NPs carefully before their practical usage in wheat and barley fields.

12.5 Application of Nanotechnology in Crop Health Management

12.5.1 Biotic Stress Management

12.5.1.1 Pathogens

Agrochemicals have transformed the wheat and barley cultivation post green revolution, but it has also provided new challenges in the form of resistance development against agrochemicals in pathogens and insect pests. Nanotechnology has strong potential for combating biotic stress imposed by pathogens and insect pests in wheat and barley. Mishra et al. (2014) examined the antagonistic potential of silver nanoparticles in controlling spot blotch disease of wheat caused by *Bipolaris sorokiniana* and observed strong inhibition towards *B. sorokiniana* infection in wheat. Later, it was demonstrated that AgNP-mediated reduction is one of the prime reasons for restricting the ingress of *B. sorokiniana* colonization on wheat (Mishra and Singh 2015). Similar evidences for the antifungal activity of Zn NPs (100 mM) have been observed in checking *Fusarium graminearum* infection and reduction a toxin produced by *F. graminearum* (deoxynivalenol) in wheat grains (Savi et al. 2015). In another study, induction of defense reaction of wheat seedlings infected with *Pseudocercosporella herpotrichoides* via inhibition of the synthesis of lipid peroxidation products have been noticed when wheat seed is treated with metal nanoparticles (Ag, Fe, Mn, Cu and Zn) (Panyuta et al. 2016). Besides NPs, nanoparticles loaded with chitosan have also been tested against *Fusarium* head blight disease in wheat and found antifungal in nature (Kheiri et al. 2016). However, antifungal behavior of chitosan nanoparticles largely depends on time period of application and growth stage of the plant. In smilar fashion, antifungal activity of the lemongrass and clove oil encapsulated in mesoporous silica nanoparticles against *Gaeumannomyces graminis* var. *tritici* fungus causing take-all disease in wheat have been observed (Sattary et al. 2020). The inhibition of *G. graminis* var. *tritici* was remarkable in seed treatments by lemongrass encapsulated in mesoporous silica nanoparticles (74.4%) and and clove oil encapsulated in mesoporous silica nanoparticles (71.27%) than pure essential oils. Similarly, Mancozeb prevented up to 70% of the disease severity in-vivo and therefore essential oils based MSNPs nanoformulations could be an ideal choice instead of the chemical fungicide for the management of takes all diseases in wheat. Dong et al. (2021) developed nanopesticides encapsulated with the fungicide tebuconazole and reported remarkable fungicidal activities against *Fusarium graminearum* and *Blumeria graminis* causing head blight and powdery mildew diseases in wheat. Further, they also observed that seed dressing with developed nanofungicide showed significant enhancement in seed germination, seedling emergence and plant height of wheat seedlings. Satti et al. (2021) synthesized titanium dioxide NPs (20–100 nm) by using the reducing and stabilizing potential of *Moringa oleifera* leaf aqueous extract. They observed that the foliar applications of TiO_2 NPs (40 mg L^{-1}) elicited agro-morphological and physicochemical modifications in wheat plants to control *Bipolaris sorokiniana* infection. The results of the present study provide strong foundation for the in-depth analysis of the positive and negative effects of the nanoparticles and modifications at the genomic level in response to the biotic stress imposed by plant pathogens.

12.5.1.2 Insect Pests

Pest infestation of wheat and barley crops start from the fields and continue through storage till the food grains consumed. Nanotechnology has advanced rapidly over the last few decades and numerous nanomaterials, with a variety of potential insecticidal properties brings new alternatives to expand the spectrum of insect pest management tool box against agricultural pests (Barik et al. 2008; Kitherian, 2017; Jasrotia et al. 2018; Ulrichs et al. 2005; Belhamel et al. 2020). Yang et al. (2009) evaluated the insecticidal properties of polyethylene glycol-coated nanoparticles loaded with garlic essential oil and reported 80% efficacy against adult *Tribolium castaneum* insect because of the slow and insistent release of the active ingredient from the applied NPs. Similarly, Stadler et al. (2017) evaluated insecticidal properties of nanostructured alumina against major pests of stored food grains and noticed insect mortality after continuous exposure to nanostructured alumina treated wheat grains (1000 mg kg^{-1}) for three days. Goswami et al. (2010) also noticed 90% of mortality of *S. oryzae* and *Tribolium castaneum* exposed for a week to hydrophilic nanostructured alumina (2000 mg kg^{-1}). Later, Stadler et al. (2012) reported that nanostructured alumina dust (94% mortality of S. oryzae adults after 15 days of exposure applied on wheat at doses ranging from 62.5 to1000 mg kg^{-1}) was more effective than Protect-It® in eliminating F1 progeny of *S. oryzae*. Similar findings were noticed by Buteler et al. (2015), when three novel nanostructured alumina dusts were applied on wheat for management of *R. dominica* and *S. oryzae*. López-García et al. (2018) also evaluated the insecticidal activity of nanostructured alumina (250–500 ppm) on *S. oryzae* using galvanized steel containers and reported that nanostructured alumina had a greater impact on insect population dynamics due to high adult mortality as well as a large reduction in progeny production. In another study, Ziaee and Ganji (2016) demonstrated insecticidal properties of silicon nanoparticles in controlling wheat grain pests. Recently, Badawy et al. (2021) biosynthesized CuO-NPs (14.0 to 47.4 nm) using the biomass filtrate from the *Aspergillus niger* strain G3–1 fungus and reported strong insecticidal properties of CuO-NPs (50 ppm) against *Sitophilus granarius* (55–94.4% mortality) and *Rhyzopertha dominica* (70–90% mortality). Overall, it appears that as compared commericial pesticides, nanoproducts provides an inexpensive, consistent and trustworthy substitute for ecofriendly management of insect pests, and such research explorations may expand the boundaries for nanoparticle-based innovations in wheat and barley insect pest management in coming time.

12.5.2 Abiotic Stress Management

12.5.2.1 Drought Stress

Nanotechnology showed great promises in mitigation of the drought stresses in both wheat and barley crops. The study was conducted by Jaberzadeh et al. (2013) to assess the effect of foliar application of titanium NPs on agronomic traits, seed gluten and starch contents of wheat under water deficit stress conditions and concluded that titanium dioxide NPs (0.02%) are beneficial in improving the wheat tolerance toward drought stress as well as agronomic traits such as gluten and starch content. Similarly, ameliorative effects of TiO_2 NPs (500–2000 mg L^{-1}) on seed germination and seedling growth of wheat under PEG-stimulated drought stress has been reported by Faraji and Sepehri (2020). Recently, same authors examine the influence of nitric oxide donor sodium nitroprusside (100 μM) in presence of TiO_2 NPs on wheat seedlings under drought stress conditions. Under severe drought stress, soil-applied TiO_2 NPs (2000 mg kg^{-1}) enhanced seedling dry weight, relative water content, catalase (CAT) activity, ascorbate peroxidase activity, and proline content. Additionally, TiO_2 NPs application showed enhanced total chlorophyll, carotenoids, stomatal conductance, and transpiration under drought stress. Interestingly, foliar application of sodium nitroprusside (100 μM) in presence of titanium dioxide nanoparticles (2000 mg kg^{-1}) can protect wheat seedlings against drought-induced oxidative damage by improving photosynthetic function and reducing reactive oxygen species. The study of Zaimenko et al. (2014) revealed the significant effect of the soil application of analcite nanoparticle in different concentration (500–1500 mg L^{-1}) and confirmed their incremental role in seed germination, seedlings growth criteria including photosynthetic pigments of wheat crop under drought stress conditions. Further, they also reported that the application of analcite nanoparticles sharply increased the activities of defense related antioxidants (carotenoids and flavonoids) in wheat seedlings under drought affected soil. In another study, Taran et al. (2017) also reported the positive effects of colloidal solution of Cu, Zn-nanoparticles in drought stress alleviation in wheat. Further, they also indicated that elevated activities of antioxidative enzymes in response to Cu and Zn NPs results in the declining the level thiobarbituric acid reactive substances and stabilization of the photosynthetic pigments, thereby enhance relative water content of leaves. Besides these changes, modifications in plant morphometric indexes (e.g. leaf area and relative water content) is also the outcome of the adaptation mechanism triggered by colloidal solution of Cu NPs and Zn NPs to mitigate drought stress problem. Similarly, in another independent study, Yasmeen et al. (2017) also highlighted that the potential of Cu NPs in enhancing the drought stress tolerance capabilities of wheat varieties. Besides this, improvement in grain yield and drought stress tolerance by mediating starch degradation, glycolysis, and tricarboxylic acid cycle in wheat varieties in response to Cu NPs have been documented by Yasmeen et al. (2017). Ikram et al. (2020) reported the foliar applications of biosynthesized SeNPs (30 mg L^{-1}) fortifies wheat crops against drought stress tolerance by promoting the development and growth of wheat plants under severe drought stress. Further, they also noticed that SeNPs is effective in elevating the morphological or agronomic attributes (e.g. shoot and root length, leaf area, leaf length, plant height, dry and fresh weight of root and shoots and number of leaves etc.) in wheat crop. However, they observed decline in wheat growth when applied SeNPs at 40 mg L^{-1}. Therefore, from aforementioned research, it is clear that nanoparticles play a essential role in ameliorating drought stress by promoting the development and growth of wheat plants in concentration dependent manner under severe drought stress. Adrees et al. (2020) observed mitigation of drought stress in wheat by soil application of iron nanoparticles. They reported that exogenous application of Fe NPs improved the photosynthesis, yield, Fe concentrations and diminished the Cd concentrations in tissues.

In case of barley crop, Ghorbanian et al. (2017) studied the genotypic response of barley to exogenous application of nanoparticles under water stress condition and concluded that Si-NPs (20 ppm) under water stress condition provides beneficial effects on yield component of barley genotypes. Later, Ghorbanpour et al. (2020) explored the potential of Si NPs on post-stress recovery performance of barley seedlings under drought stress during vegetative growth and found that soil application of Si NPs (125 mg L^{-1}) provide post-drought recovery of barley plants via modifying plant morpho-physiological and antioxidative attributes and synthesis of specific metabolites. Behboudi et al. (2018) observed positive and incremental effect of chitosan nanoparticles (60 and 90 ppm) on yield and yield components of barley under late season drought stress. Further, it has been noticed that chitosan NPs elevated the relative water content, proline content, grain protein, 1000-grain weight, CAT and SOD in plants under drought stress and therefore assisted in the alleviating the harmful effects of drought stress in barley crop.

12.5.2.2 Salinity Stress

Farroh et al. (2020) studied the impact of chemically synthesized zinc oxide nanoparticles (21–41 nm) on saline stressed wheat and marked increase in plant height, biochemical parameters and antioxidant defense mechanism with 0.25 ppm ZnO NPs relative to control under saline stress conditions. Similarly, El-Saber et al. (2021) also investigated the effect of foliar application of magnetite nanoparticles (22.05 nm) at different concentrations (0, 0.25, 0.5, and 1.0 ppm) to improve salinity tolerance. They observed that the Fe NPs (0.5 ppm) helped the wheat plants to alleviate the effects of salt stress by activating growth, chlorophyll content, SOD, glutathione, and soluble proteins. The toxicological and positive impact of biocompatible CuO nanoparticles (1 ppm) on the growth and yield of wheat genotypes under saline environment have also been studied by Mahdi et al. (2020). They concluded that field application of CoNPs (1.0 ppm) had positive effect on wheat plant growth attributes and able to reduce MDA content, and increase chlorophyll, glutathione content and accumulation of SOD band and polypeptides, which ultimately responsible for enhancing the wheat tolerance towards to saline stress. In barley crop, Habibi and Aleyasin (2020) provided the research evidence that SeNPs can promote the growth of barley seedlings under salt stress. The results of their study clearly indicated the application of Se NPs (100 mM) increase total phenolic levels, and resulted in significant reduction of MDA contents, which could influence the metabolism and be responsible for the increasing shoot dry weight under salt stress.

12.5.2.3 Heat Stress

To overcome the adverse effects of heat stress, Borai et al. (2017) synthesized magnetite (Fe_3O_4) nanoparticles by using hydrothermal method and evaluated for consecutive field experiments on wheat plants under heat stress conditions. They found 0.25 ppm MNPs as the optimum concentration able to enhance the yield as well as quality of wheat grains. Further, they also mentioned that the enhancement of yield parameters and quality may be due to the increment in the determined biochemical markers (GSH and GST) to counteract heat stress. The positive influence of magnetite (Fe NPs; 50 nm) and zinc oxide (Zn NPs; 80 nm) and nanoparticles in the alleviation of heat stress in wheat plants has been observed by Hassan et al. (2018). They revealed that application of Zn NPs (10 ppm) and Fe NPs (0.25 ppm) protect plants by enhancing the activities of antioxidant enzymes (Glutathione S transferase, superoxide dismutase, peroxidase and catalase), and decreasing lipid peroxidation product malondialdehyde. Similarly, Iqbal et al. (2019) studied the effects of AgNPs on wheat growth and development. They concluded that AgNPs (50–75 mgL^{-1}) improve morphological growth of wheat plants under heat stress.

12.5.2.4 Heavy Metal Stress

Heavy metal pollution is not only a hazard to wheat and barley crop but also an important worldwide environmental concern (Kushwaha and Kashyap 2021). In this connection, experiments have been performed by Konate et al. (2017) to explore the physiological mechanisms of magnetic nanoparticles (Fe_3O_4 NPs) for alleviating heavy metals (Pb, Zn, Cd and Cu) toxicity in wheat plants. They reported that Fe_3O_4 NPs (2000 mg L^{-1}) decrease heavy metals uptake and lessen their toxicity by activating the protective mechanism that can decrease the root growth inhibition and assuage oxidative stress induced by heavy metals in the wheat seedlings. Moreover, this alleviating effect of nano-Fe_3O_4 is due to adsorption capacity of heavy metals which generated different kinds of electrostatic magnetism between negatively charged adsorption sites and heavy metal cations. In similar fashion, ZnO NPs also reported to decrease Cd intake in wheat (Hussain et al. 2018). Khan et al. (2019) reported the fertilization effect of ZnO NPs (100 mg/kg) in improving wheat growth under Cd stress in different soil moisture conditions. Further, they highlighted that ZnO NPs significantly reduced the Cd accumulation in tissues and grains by reducing the soil bioavailable Cd and its accumulation by roots. Rizwan et al. (2019) studied the effects of seed priming with zinc oxide (ZnO) and iron (Fe) nanoparticles (NPs) on the growth and cadmium (Cd) accumulation by wheat. Their study depicted that the seed priming with ZnO NPs (100 mg L^{-1}) and Fe NPs (20 mg L^{-1}) decreased Cd accumulation in wheat grains and enhanced plant height, spike length, and dry weight of shoots, roots, spikes, and grains under Cd-contaminated soil. They also noticed that both the NPs positively affected the photosynthesis of wheat and reduced the electrolyte leakage and superoxide dismutase and peroxidase activities in leaves of Cd-stressed wheat. In another study, Adrees et al. (2020) provided experimental evidence for the role of Fe-NPs in improving the growth and physiology of wheat and reduction of the Cd contents in various tissues of wheat including wheat grains. It is important to mention here that the authors also observed that NPs alleviated the oxidative stress in leaves and the efficiency relies on the NPs concentrations applied in the soil. The aforementioned research findings clearly depict that NP application has a potential for alleviation of heavy metal soil contaminations.

12.6 Nanotechnology in Stress Diagnosis

Nanotechnology offers a plenty of options for researchers engaged in the timely and rapid detection, identification and monitoring of crop health (Kashyap et al. 2017). Such rapid detection technologies with high precision, sensitivity and selectivity for detecting both abiotic and biotic stresses are indispensable to avert disease spread and diminish losses to get optimal productivity and food security (Kaur et al. 2020; Kashyap et al. 2011, 2019b; Sharma et al. 2017). Conventional laboratory assays employed for wheat and barley stress diagnosis are time consuming, laborious and more over need complex sample handling skills. In this context, functionalized nanoparticles emerged as an ideal choice for designing and development of on-the spot phytopathogen detection devices with smart sensing capabilities (Kashyap et al. 2016, 2020a). Singh et al. (2020) applied nanogold-based immunosensors amalgamated with surface plasmon resonance (SPR) technology to detect *Tilletia indica* infection in wheat seeds. Campagnoli et al. (2011) developed electronic nose (EN) equipped with metal-oxide-semiconductor (MOS) sensors for the screening and recognition of durum wheat naturally contaminated by deoxynivalenol toxin. In another study, Eifler et al. (2011) developed metalloporphyrin-based E-nose for the qualitative detection of *Fusarium* infected wheat grains with an accuracy of 80%. The application of electronic nose technology has been explored for the detection and discrimination of rusty grain beetle from red flour beetle (RFB) in wheat by Wu et al. (2013). Further, they reported that the E-nose technology is able to detect RFB in wheat (20 insects kg^{-1}) at 14% and 16% moisture content in stored grains. In view of the aforementioned limited reports, it is clear that nanotechnology has strong potential for the detection and diagnosis of plant pathogens and pests in wheat and barley crops. At present research progress in this front is in preliminary stage and real potential of nanotechnology in surveillance, monitoring, and detection of biotic and abiotic stress in wheat and barley crops is still anticipated.

12.7 Research Gap and Future Challenges

Nanotechnology being a fascinating and novel technology, able to modify the physical and chemical characteristics of a substance at nano-level, holds great promise in the field of wheat and barley cultivation. In recent years, the role of nanotechnology has been experienced for diverse applications in wheat and barley including the enhancement in the growth, quality, and quantity of their end products under different environment vagaries. There are several below mentioned researchable issues that need to be addressed in light of the upcoming innovations in the field of nanotechnology and their application for promoting sustainability in wheat and barley health management.

- An exogenous application of NPs and nanoproducts largely depends on the size and dosage standardization and moreover, their corroborating role in mitigating biotic and abiotic stresses in wheat and barley are still in nascent stage and under controlled in-vitro and glass house conditions only. Under such circumstances, extensive research and additional field trials at large scale are required before implementing this technology for attaining sustainable production.
- NPs reported as excellent materials for seed priming or seed coating in wheat and barley. However, caution is highly warranted in their usage and requires appropriate regulations based on inclusive research, not only in these two crops, but in other allied sectors too. Additionally, necessary information regarding evaluation of NPs for priming should be generated as concentration, size and exposure time of NPs can cause non-target effects in the form of seed germination inhibition, stunted plant growth and deleterious alterations in the metabolism, cell structure and microbiome of wheat and barley genotypes etc.
- Wheat and barley cultivation is the part of the ecosystems and therefore directly influenced by application of nanomaterials. Under such circumstances, it becomes mandatory to decipher the mechanisms of action of nanomaterial and fabrication of nanomaterials that are safe and within permissible residual limit for the field appplication. Moreover, legal frameworks for industrial production of nanomaterials, treatment of industrial waste, and agricultural applications, together with assessment of NPs fate in the environment should be developed and implemented.
- NPs can be utilized for biotic and abiotic stress management in wheat and barley crop. Besides direct application of NPs, they can be explored as protectant and nanocarriers for insecticides, herbicides, fungicides, and RNA-interference molecules for better management of wheat and barley crop. In addition, innovations in the development of nanosensor seem quite useful for designing of precise and sensitive diagnosis tool, which ultimatly pave way for timely stress management under field conditions. Therefore, it will be exciting to discover the application of nanosensors for detecting stress problems occurred in wheat and barley fields as well in grain storage facilities.
- Several published reports indicate the key role of NPs as alternative for the genetic transformation of plants. At present, this possibility is less explored in case of wheat and barley and nanomaterial-mediated transformation for generating transgenic wheat and barley with anticipated traits demands further research investigation.

12.8 Conclusion

The information presented in this chapter clearly provide information on the potential of nanoparticles to stimulate plant growth and accomplish better health by triggering positive impact on seed germination, plant growth, and grain yield. Therefore, a transformation from testing and exploiting existing NPs for fabricating specific nanoparticles based on farming demand will enable the wise use of nanotechnology in sustainable wheat and barley production especially under stressed environment. However, understanding the positive and negative impacts of nanotechnology derived products on the growth and development of wheat and barley is essential for the assessment of plausible environmental risks to food safety and human health; because these crops are vital food source for ever expanding human population.

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Part III

Expanding Horizons in Resource Management

13 Integrated Management Practices for Incremental Wheat Productivity

B. S. Mahapatra and Prithwiraj Dey

13.1 Introduction

Domestication of wheat in a landmark in the agricultural history of the world. It was one of the prime drivers for the shift of mankind from hunter-gatherers to self-dependent farmers (Charmet 2011). Wheat plays an even greater role in quenching much of the world's hunger today. Globally wheat occupies an overwhelming 215 mha of the cultivated land area leading towards its crown of highest area coverage in the world among all the cultivated crops in the world (FAO 2013). It is grown all over the world due to its successful adaptations in wide agro-ecological conditions across the globe. Wheat is a major staple food for nearly 2.5 billion people in the globe. After wheat contributes more than fifty per cent of the protein intake in the lower and middle-income countries (Shewry and Hey 2015).

Wheat had seen a paradigm shift in productivity across the world over the last century and had witnessed multiple green revolutions in several countries. Despite such a record, wheat production and productivity are now under even more pressure to satisfy the growing demand of the world. Recent studies have emphasised that the world is in a need to produce 60–100% more food as of today by 2050 to supply food to 9 billion population (FAO 2013). Another study suggests that there is a need for production enhancement by 70% within a span of 2007–2050 (van der Sluijs and Vaage 2016). However in the last few decades, all over the world, wheat productivity, as well as quality, has increased significantly due to untiring efforts of the scientists, breeders and policymakers (Edgerton 2009). But, nowadays, the yield

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plateau or yield stagnation or even declining the yield per unit of land, are of common occurrence in many instances (Ray et al. 2012).

India's foodgrain production has also bubbled a lot during the post green revolution era. Even due to the exemplary contribution of wheat production in the green revolution, it is popularly called the great wheat revolution (Chakravarti 1973). It was beyond doubt that the green revolution has done a lot for the country but the effects of the green revolution had started to fade out reportedly within its 30 years from the 1990s. In spite of good rains year after year, lump sum fertilizations the wheat production increased by only 1.7% per annum in comparison with yearly 2.6 to 3.5% increase during initial years of green revolution from 1960 to 1980 (Daniel 2000). Such pieces of evidence are in favour of the yield stagnation in the country. Currently, the country's population is growing at a pace of around 2% per annum ad it is really a growing concern to sustain the food security of the country under the immense population pressure (World Bank 2019). The cultivated area in the country has not increased after independence and even there is a possibility that infrastructure building, dam salinization, soil erosion may reduce it further concentrating the pressure on the food grain production (Ramadas et al. 2019). Increased occurrence of aberrant climatic events, limited water supply, chances of disease pest outbreak are even more concerning factor today. In such a condition, maintenance of food security in the country as well as in the world largely depends on how well we can manage the largest area occupying crop. The current chapter deals with several concerns in the wheat production in India and suggests a range of management strategies to improve productivity as well as overall production of wheat in India in a sustainable manner.

13.2 Wheat Production Scenario at Present

13.2.1 Global Scenario in Wheat Production

Wheat is globally grown in a large area of 215 mha nearly equal to the total land area of Greenland, distributed all across the world. The total valuation of annual wheat trade in the world is nearly 50 billion USD (CGIAR 2017). Around 2.5 billion people across 89 countries eat wheat as their staple food. According to FAO, to cope with the population pressure, developing countries should increase wheat production by 77% within 2050 (FAO 2009). Out of that, more than 80% to be contributed by vertical expansion by increasing productivity (FAO 2009). Wheat yield increased from 3.3 tha^{-1} to 7.7 tha^{-1} within a few years from 1961 to 1984.

However, after that, the yield increment effect was a kind of, diluted as evidenced by the wheat productivity in 2011 which was 7.6 tha^{-1} (Curtis and Halford 2014). It was partly due to the yield stagnation in wheat that record yield (651 mt) has now been overtaken with rice (672 mt) and maize (844 mt) in a significant proportion of area (FAO 2013). Table 13.1 shows the status of the major wheat-producing countries in the world in 2017-18.

Table 13.1 Wheat area, production and productivity status of major wheat growing countries (non-exhaustive list) in the world

Countries	Area (mha)	Area contribution (%)	Production (mt)	Production contribution (%)	Productivity (t ha^{-1})
China	24.51	11.1	134.33	17.6	5.48
India	29.58	14.0	99.70	12.9	3.37
Russian Federation	27.34	12.4	84.99	11.1	3.11
United States	15.19	6.9	47.35	6.2	3.12
Canada	8.98	4.1	29.98	3.9	3.34
Ukraine	6.64	3.0	26.98	3.5	4.06
Pakistan	8.97	4.1	26.67	3.5	2.97
Australia	12.25	5.6	21.30	2.8	1.74
Turkey	7.80	3.6	21.00	2.8	2.69
Kazakhstan	11.91	5.4	14.80	1.9	1.24
World	220.00	–	763.06	–	3.47

Adapted from Ramadas et al. (2019)

13.2.2 Indian Scenario in Wheat Production

In India, spring wheat is grown in the Rabi or winter season. Uttar Pradesh is marked with its largest contribution in the national wheat area with alone accounting for 9.75 mha or 32% of the country's national area under wheat. It is followed by Madhya Pradesh, Punjab, Rajasthan, Haryana etc. with 18.8, 11.5, 9.8 and 8.4% share in the national wheat area respectively. The area under wheat in the country has shown a slight increase of nearly 5% in the last decade. The national production of wheat has also increased by 8.2% from 2012–13 to 2017–18. It was mainly attributed to a slight increase in the area and not by increasing the yield per hectare as confirmed by only a marginal change in the national productivity from 3009 to 3100 kg/ha over the same period. The Table 13.2 shows the status of the major wheat producing states in India during 2017–18.

However, the country's majority of the wheat production is coming from the wheat growing zones, the productivity in the traditional areas are nearly stagnated. But at the same time, productivity in the wheat has grown up significantly in the non-traditional areas indicating a better response to the applied inputs and technologies (Table 13.3). Such trend shows the possibility of the second green revolution in the country specifically through the area as well as productivity expansion. In traditional areas, the yield stagnation has become a severe issue to be addressed today. In this chapter, such problems of yield stagnation and the possible ways out are discussed in the light of available literature, data and technological know-how.

Table 13.2 Wheat area, production and productivity status of major wheat growing states (non-exhaustive list) in India

States	Area (mha)	Area contribution (%)	Production (mt)	Production contribution (%)	Productivity (kg ha^{-1})
Uttar Pradesh	9.75	33.6	27.93	29.6	2867
Madhya Pradesh	5.73	19.8	16.32	17.3	2843
Punjab	3.51	12.1	16.61	17.6	4738
Rajasthan	2.98	10.3	9.31	9.8	3133
Haryana	2.55	8.8	11.24	11.9	4407
Bihar	2.08	7.2	4.86	5.1	2339
All India	29.04	–	94.57	–	3100

Adapted from Ramadas et al. (2019)

Table 13.3 Wheat area, production and productivity changes in 2017–18 with respect to base year 2008–09

States	Changes in area	Changes in production	Change in productivity
Traditional wheat growing areas			
Punjab	−0.40%	2.21%	2.61%
Haryana	2.21%	−0.93%	−3.01%
Rajasthan	12.99%	14.62%	3.12%
Uttar Pradesh	0.94%	−4.77%	5.23%
Madhya Pradesh	26.76%	72.72%	5.38%
Non-traditional Wheat Growing Areas			
West Bengal	−8.33%	−5.94%	22.90%
Assam	−52.35%	−43.40%	16.39%
Jharkhand	50.99%	70.04%	12.01%
Uttarakhand	−9.89%	−4.64%	10.76%
Himachal Pradesh	−4.26%	24.79%	19.28%
Karnataka	−25.30%	−13.23%	15.64%
Chhattisgarh	0.59%	13.22%	15.59%

Adapted from Ramadas et al. (2019).

13.3 Assessment of Production Constraints

13.3.1 Genetic Constraints

India has witnessed a great achievement in the development of the high yielding varieties in the past few decades. The country has become the world's largest wheat producer from a majorly wheat importing country. The scientific works of wheat improvement in India started way back in the initial years of twentieth-century with successful pure line selections from local landraces (Greveniotis et al. 2019). A range of exotic breeding materials was used for crossing with local races in the 1920s which had yielded several high yielders of Pb, NP series. Other challenges like the higher incidence of diseases like rust and pest pushed breeders further in developing resistant materials. Such varieties, despite of all good efforts, were bound by yield barriers until 1964–65. That yield barrier in wheat varieties was broken by legendary Dr. N. E. Borlaug and Dr. M. S. Swaminathan with the introduction of dwarf, input responsive, photo insensitive varieties and resulted in the 'Green Revolution'. High yielding varieties like Chhoti Lerma, Kalyan Sona, Sonalika, Safed Lerma etc. gained quick popularity within 1970. These varieties were followed by further improved varieties like HD2329, HD 2285, WH 147, HD 2009 etc. These varieties were also quickly adopted by the farming community.

But once again, a yield limit set by HD 2329 could not be broken for a very long time until Veery based and 1B/1R based materials came into play. Varieties like PBW 343, PBW 373, WH 542 were developed breaking the yield barriers. Such varieties are still in the farmers' field, and breeders are in a stuck condition again to break the new yield levels. From the last decade, it has really become challenging to keep pace with the growing demand for wheat with the present genetic potentials. For ensuring a sustainable yield increase, at least 50% must come from the improved genetic materials while the other half may be contributed to the agronomic management practices. Breaking the yield barrier in wheat genetic material that is currently available with the country, has become more relevant because other components of barrier-breaking, seem to be quite exhausted for the last few decades as stated below:

- Use of fertilizers has approached to optimum levels to get any economic yield benefits. Especially, in the NWPZ, more and more farmers have adopted recommended fertilization practices. However, in other zones. There may be a gap in the recommended and adopted practices. Further, excess nutrients and low organic matter use is challenging the sustainability of the yield in high yielding areas.
- With the major expansion of the irrigation facility, there is no large gap to harness with the advent of irrigation in the country level.
- Adoption of new varieties is also approaching towards saturation. So, better seed replacement ratio will not be a player to give a yield boost in national as well as regional levels.

In such circumstances, a paradigm shift in the breeding approaches is much needed to break this status quo in the wheat development.

13.3.2 Crop Management Constraints

13.3.2.1 Fertilizer Use and Nutrient Imbalance

After the green revolution in the 1960s, within the next twenty to thirty years wheat yield in India has witnessed a stagnation or a decline in most green revolution affected areas (Duxbury et al. 2000). Majumdar et al. (2013) has reported from a wide-spread study in the Indo-Gangetic Plains that response of wheat to three major nutrients such as N, P and K ranged from 500–4750 kg/ha, 67–2806 kg/ha and 0–2222 kg/ha, respectively. Such wide variations in the yield response indicate huge variations in the nutrient supplying capacities of the soil. Widespread variations in soil fertility within six major wheat growing areas in Punjab was also pointed out by Khurana et al. (2008). However, recommendations in the country are generally made by the yield response data averaged over a large geographic location. Such broad recommendations are not a good fit where a huge variation in the soil fertility status persists. Blanket recommendations are often unable to address high or low fertility areas and thus create a range of yield response arising from nutrient imbalance. Declining wheat productivity, yield stagnation have been many times found to have associations with poor management of the variabilities in soil fertility regime (Tiwari 2006; Meena 2020).

Imbalance in the nutrient regime due to these faulty application of nutrients in the farmers' field has been also well addressed by many researchers. Surveys conducted in the wheat growing areas of the Indo-Gangetic Plains revealed that farmers often tend to apply more N and P, sometimes more than the recommended doses. While completely or partially ignoring the K and other nutrients such as S, Zn, B etc. Tiwari (2006) has reported the severity of the S, Zn and B deficiencies and associated them with yield stagnation and decline in the rice-wheat system. About 50% of the samples in the study found to be Zn deficient while B deficiency was found in 33% of the samples. About 250 districts in several wheat growing zones were found to have prevalent S deficiencies (Tiwari 2006). Shukla et al. (2012) has suggested that alone improper management of Zn deficiency causes a loss of food grains amounting 18.4 mt. Deficiency of K is one of the major reasons for the yield stagnation in the Indo-Gangetic Plains (Bhatt et al. 2016). So, under the purview of these problems, it is quite clear that a properly planned nutrient schedule is much needed to maintain the system sustainability and incremental wheat productivity.

13.3.2.2 Built-Up of Disease and Pests

Wheat is often grown under plentiful resource conditions with high nitrogen fertilization and moist soil conditions created by frequent irrigation practices. Such an environment is quite favourable for the outbreak of disease and pest. Rice-Wheat system followed in a huge chunk of land has already created a monoculture like systems without significant changes in the host crop over a long time. Such systems, in the long run, have turned into the breeding ground of diverse insect-pests and diseases. Major pests and diseases of the wheat which are of national significance are given in Table 13.4.

Pests and diseases that were minor pests and of less importance, have grown as pests and diseases of national importance today. Such disease pest causes significant damages each year. In the absence of horizontal resistance, varieties of today are more and more prone to the dynamic pest complex. Investment on the plant protection materials is increasing day by day with stagnated or even declining yield. Such situations are one of the reasons for lower profitability as well as the greater environmental risk associated with the wheat agro-ecosystem in India.

Table 13.4 Major pest, diseases of the national importance of wheat

Pest and diseases	Scientific name/causal organism Insects and mites	References
Shootfly	*Atherigona naqvii*	Sood et al. (1970)
Wheat aphid	*Sitobian avenae*, *Sitobian miscanthi*	Ahmad et al. (2016)
Army worm/cut worm	*Mythimna separata*	Prasad and Babu (2016)
American pod borer	*Helicoverpa armigera*	Patel and Tiwari (2018)
Pink stem borer	*Sesamia inferens*	Singh (2012)
Brown mite	*Petrobia latens*	Nogia and Sharma (2003)
Termite	*Odontotermis obesus* *Microtermes obesi*	NIPHM (2014)
Nematodes		
Seed gall Nematode	*A. tritici*	Parveen et al. (2003)
Tundu or yellow ear rot	*Rathaybacter tritici* + *A. tritici*	NIPHM (2014)
Cereal cyst Nematode	*Heterodera avenae*	Bhatti et al. (1981)
Root knot Nematode	*Meloidogyne* spp.	Singh et al. (2010)
Diseases		
Brown rust	*Puccinia recondita*	Bhardwaj et al. (2019)
Black rust	*Puccinia graminis tritici*	Prasad et al. (2020)
Yellow/Stripe rust:	*Puccinia striiformis*	Bhardwaj et al. (2019)
Karnal bunt	*Tilletia indica*	NIPHM (2014)
Loose smut	*Ustilago tritici*	NIPHM (2014)
Powdery mildew	*Blumeria graminis*	ICAR-IIWBR (2020)
Flag smut	*Urocystis agropyri*	Kashyap et al. (2020)
Hill bunt	*Tilletia tritici*	NIPHM (2014)
Alternaria leaf blight	*Alternaria triticina*	NIPHM (2014)
Footrot	*Pythium graminicolum*	ICAR-IIWBR (2020)

13.3.2.3 Weed Flora Shift and Resistance

Introduction of the dwarf wheat varieties during the green revolution in the country along with high input scenarios have changed the weed flora in wheat growing regions multiple times within a short span of time. The dominance of broadleaf weeds in the 1960s had shifted to a complex flora of broadleaf and grassy weeds within the first 10 years of the green revolution. Finally the flora shift towards grassy weeds especially in the favour of *Phalaris minor* in the late 1970s (Chhokar et al. 2012). Introduction of herbicides changed the flora again to complex weeds in the 1980s which again shifted towards *Phalaris* with the emergence of herbicide resistance (Malik and Singh 1995b).

Status of the herbicide resistant weeds all over the world is rather alarming. In Table 13.5, some high risk herbicides group and number of resistant weeds all over the world are represented.

In the pre-green revolution era in India, local wheat varieties were quite competitive to weeds and had a greater suppressing ability under low input conditions. More susceptible dwarf varieties with high inputs introduced weed seeds and

Table 13.5 World scenario of herbicide resistance in relation to herbicide mode of actions

Herbicide mode of action	Example	No. of resistant species	% of world total	Risk of resistance
ALS inhibitors	Chlorimuron	165	32	High
PSII inhibitors (triazines)	Atrazine	74	15	High
ACCase inhibitor	Quizalofop	48	9	High
Auxins	2,4 D	41	8	High
PSII (Ureas)	Isoproturon	29	6	Medium
PPO inhibitors	Carfentrazone	13	3	Medium
Microtubule assembly inhibitors	Pendimethalin	12	2	Medium
Carotenoid synthesis inhibitors	Tembotrione	6	1	Medium
PSII inhibitors (nitriles)	Ioxynil	4	<1	Very low
Glutamine synthesis inhibitors	Glufosinate	4	<1	Very low

Adapted from Ngow et al. (2020).

non-scientific use of herbicides in the post green revolution era have bred weeds as a menace to production nationwide. The average loss in the wheat yield per annum across different wheat growing regions ranges from 20% to 32% (Mongia et al. 2005). Even extreme cases of crop failure were reported in mid-nineties due to the emergence of herbicide-resistant *Phalaris minor* (Chhokar and Malik 2002). Only *Phalaris* and wild oat, belonging to the grass family and being very difficult to identify once mixed with seeds, cause 10–80% yield loss depending upon the situation. Yellow thistle, a prominent weed in wheat in the pre-green revolution era, has now become obsolete and replaces with more difficult to control weeds such as *Phalaris minor*, *Rumex dentatus*, *Medicago denticulata* under most irrigated wheat ecosystems (Balyan and Malik 2000; Chhokar et al. 2006). Under light textured soil, problem of wild oat is prominent. Evolution of multi-resistance in *Phalaris* has made it a single prominent limitation in wheat cultivation in entire north western India.

13.3.3 Natural Resource Degradation

Though the green revolution in India was much appreciated for the sharp boost in the productivity, area and total production of mainly rice and wheat, it came with its own costs of the degradation of natural resources. Poor understanding and negligible considerations for the sustainability of such huge production benefits may be one of the prime reasons for accelerated degradations of soil and water systems due to intensive and ill-managed rice-wheat production system. In the country, nearly 4.5 mha salt-affected area is under wheat cultivation posing a greater challenge for the canal irrigated areas (Foley et al. 2019). With the passage of the time, faulty schemes and irrigation practices especially in the canal irrigated area are converting more and more land to poor salt-affected soil and thus declining productivity and profitability (FAO 1997; Shrivastava and Kumar 2015). Reclamation of such salt-affected soil is a strategic option by deploying optimum drainage and application of amendment in alkaline regions. However, the pace of such strategic reclamation is negligible in the case of wheat (Ramadas et al. 2019). Availability of quality water for the irrigation purpose is another prime issue in the way of the sustainability of wheat cultivation in the country. Dangerously falling water levels due to indiscriminate use of groundwater in states like Punjab, Haryana etc. as well as peer population pressure on the water resources resulting in less and less per capita availability of water with each passing year. In such a scenario, a crop like wheat which needs a good amount of irrigation for considerably high yield is bound to suffer in the coming days.

13.3.4 Changing Climatic Conditions

Global climate change is a reality of today and evidence of significant changes in the long term averages of weather conditions are being reported from all over the world (IPCC 2014). It has been suggested by several workers that extreme climatic events will be more and more frequent due to the changing climate scenarios (Gibelin and Déqué 2003; IPCC 2013; Swain et al. 2014). Major causes of climate change induced yield reduction in wheat may be listed as forced maturity and shortening of developmental phases under heat stress. Such shortening of growth phases may result in the reduction of light interception and low photosynthates accumulation which is often translated to lower productivity (Modarresi et al. 2010). As wheat is a C3 plant, under higher temperature, photo-respiration become much prominent and reduce net photosynthesis. Temperatures higher than 35 °C reduces the carboxylation activity of Rubisco and enhances the oxygenase activity in wheat (Sage and Kubien 2007). Such oxygenation activity reduces the carbon-di-oxide reduction and increases the loss of photosynthates through photo-respiration.

Plants may also be subjected to the aberrant weather conditions such as heatwaves during vegetative phases. Such instances may result in alteration in the hormonal balance, closure of stomata, reduction of photosynthesis and even death sometimes (Zafar et al. 2018). Heat stress during flowering stage may cause 90% sterility in the florets resulting in devastating yield loss in wheat (Demotes-Mainard and Jeuffroy 2004). Heat stress is often coupled with significant water stress. Under absence of irrigation facility, such water stress alone or in combination with heat stress may cause in significant yield loss in wheat. Water stress at CRI stage of wheat causes reduced tillering and ultimately reduced the number of ears per and lesser grain yield per plant.

13.4 Ways and Means to Improve the Productivity of Wheat

13.4.1 Genetic Improvement

Genetic improvement of any crops depends upon the explorable variability in the genetic makeup in the species or even in the genus (Govindaraj et al. 2015). Collection and maintenance of diverse genetic materials in the germplasm for the future breeding programme is of utmost importance to break the stagnating condition. The genetic diversity present in the cultivated wheat's D genome is way lesser than the D genome of diploid wheat species (Feldman and Levy 2012). In a similar manner, a lot of genetic diversity has been ignored in the development of tetraploid wheat species (Laidò et al. 2013). Such unutilized genetic diversity in the ancestral wheat genotypes may be utilized for the development and of new varieties. As experienced in the past, development of genetic material through the international collaboration for exploring diverse genetic diversity present in far sub-continents, was much successful for Norin 10, Verry based varieties. Such a concept of exploring wild diversity worldwide still holds promise for tomorrow (Rajaram 2001).

In the past, research activities to develop commercial hybridization in wheat could not be successful in several countries. However, in present times, there is again a wave for the development of such techniques using chemical sterilant as well as using cytoplasmic male sterility (Pingali 2012). Theoretical evidence shows a possibility of 15–20% yield increase in hybridized wheat due to heterosis (Troyer and Wellin 2009; Whitford et al. 2013). Exploring such potentials can immediately provide a boost in the world wheat production. Hybrids can also provide heterosis for other secondary characters such as stress tolerance, better root growth, higher water use efficiency etc. (Prey et al. 2019).

The yield of plants may also be dependent upon our perception of ideal plant type. As such perceptions mould breeders' selection of varieties with desired characters. In the case of rice, the ideal plant type of IR8 was debunked by a team of breeders led by Dr. Khush for breaking the yield barrier and paving the way for super rice (Khush 1987). The success of such new plant type (NPT) concept holds hope for wheat too for breaking the yield limit of PBW 343 (Singh et al. 2017). Varieties like DL-1266-5 with robust plant type and dark, lush green foliage has been reported to break the yield limits of PBW-343 in New Delhi by Singh et al. (2005). Recent successful breeding of double dwarf wheat variety HD 2967 has gained immense popularity among farmers over long grown PBW 343 due to its higher yield and resistance to aphids, now being dominant in Punjab region (Pavithra et al. 2017). However, wide testing of such super wheat varieties is needed all across the country. Similar lines with Lr9 and Lr19 genetic combinations are being worked under the supervision and lead of CIMMYT on an international scale (Marasas et al. 2003).

In India, the genetic variability of wheat in farmers' field is limited and mostly confined to a few popular varieties (Gupta and Kant 2012). With the significant homogeneity of wheat gene base in the large area under cultivation, a devastating outbreak of disease-pest is only a matter of time. Alone PBW 343 covers 7 mha of wheat area in India (Yadav et al. 2010). Further, PBW 343 is much susceptible to Ug99 strain of black rust, spot blotch and powdery mildew (Singh et al. 2013). Upon favourable weather conditions, massive damage due to the outbreak of a single disease or pest is a serious threat to the country's food security. In a number of varieties, presence of Lr13, Lr34 and Lr46 genes were found to be much related to the resistance for leaf rust (Imbaby et al. 2014). Incorporation of such genetic base in the traditional breeding programme and broadening the horizontal resistance base is much desired to avoid the catastrophic future. Many of the wheat growing regions are stressed by the terminal as well as midseason heat stresses. With the advent of the changing climatic scenario, breeding for heat-tolerant lines should be taken as a priority research. A number of high yielding varieties such as Raj 3765, HUW 234, HD 2643, DBW 14 etc. are quite adopted to the rainfed growing conditions in Madhya Pradesh, Rajasthan and Uttar Pradesh. Such varieties have a good degree of heat tolerance in their genetic makeup (Joshi et al. 2007). Incorporation of these genetic sources to transfer the desirable heat tolerance characters in popular varieties must be taken into consideration.

Advanced breeding techniques with marker-assisted selection, QTL mapping as well as biotechnological approaches for new generation breeding must also be explored over and above traditional breeding techniques (Collard and Mackill 2008). Such technologies have huge potentials to create genetic variability, identify and transfer specific genes related to desired traits within a short period of time. However, traditional breeding may not be substituted with modern breeding but may be supplemented and work together for a paradigm shift in wheat genetic improvement.

13.4.2 Better Crop Management Practices

13.4.2.1 Crop Establishment and Tillage

Wheat is grown mainly under Rice-Wheat system in most of South Asia and China. Over the last few decades, especially after the green revolution in India, Rice-Wheat system has emerged as the largest cropping system in the region accounting for nearly 40% of the wheat area and 30% of the rice area in the country (Gathala et al. 2011). From several long term experiments, Ladha et al. (2015) have examined several production constraints in the rice-wheat system in Indo-Gangetic plains and have identified prime causes of yield stagnation and decline such as degradation of the soil-water resource base and inefficient nutrient management. In the majority of the rice-wheat area, rice is grown under the puddled condition for several benefits of puddle transplanting in rice (Sharma et al. 2015). However, such activity is deleterious for wheat following rice in the same land. Adverse effects of puddling on soil physical properties including sub-optimal aeration, development of hardpan, destruction of soil structure, causes significant yield losses in wheat in both direct as well as indirect ways (Hobbs and Gupta 2003; Kumar et al. 2008; Sharma et al. 2015). Such practices are hugely labour intensive and dependent upon availability of water increasing the risk of natural resource depletion as well as elevating the cost of cultivation (Ladha et al. 2009).

Such problems may be addressed through the adoption of conservation agriculture practices in the rice-wheat system. Growing rice and wheat under zero tilled or reduced tilled conditions is feasible in most of the wheat growing zones in the country (Hobbs and Gupta 2003; Ladha et al. 2009; Sharma et al. 2015). Ladha et al. (2009) had also reported a significant increase in the system productivity and profitability when puddled-transplanted rice was switched with direct-seeded rice and wheat is sown under zero tilled raised bed system. Such production system was found to be highly input efficient. Zero till planting of wheat has quickly gained popularity in the farmers of the Indo-Gangetic plains owing to advancement of the wheat sowing especially in areas where rice is late harvested. Total area under zero tilled wheat and reduced tilled wheat in Indo-Gangetic plains was estimated to be 1.6 mha in 2004–05 (Shoran 2005). Further, zero tilled wheat reduces the incidence of problematic weed *Phalaris minor* in wheat (Chhokar et al. 2007a; Erenstein 2009; Jat et al. 2009; Saharawat et al. 2010). However, in such scenarios, rice is still grown under puddled condition. For the realization of the potential benefits of conservation agriculture, rice in the rice-wheat system must be switched to conservation mode from conventional (Kumar and Ladha 2011). Surveys conducted in the state of Punjab and Haryana, major wheat producing provinces of India, reveal 34% user adoption of zero tillage in Haryana and 12% in Punjab (Laxmi et al. 2007a). Conservation agriculture in the rice-wheat system has been repeatedly reported to improve physical, chemical and biological properties of soil (Sharma and Acharya 2000; Bazaya et al. 2009); improving water and nutrient use efficiency; increasing in farm productivity and profitability in a sustainable manner (Yaduvanshi and Sharma 2008). Higher water-stable aggregate stability, lower bulk density, higher organic carbon content with significantly higher available nitrogen, phosphorus and potassium in long term conservation agriculture based study in the rice-wheat system had been reported by Vargas Gil et al. (2009). Kumar et al. (2008) have reported 8% yield increment in wheat when previous rice was cultivated under DSR system in a long-term study. Puddled rice can also delay wheat sowing due to excess moisture in the field leading to a yield penalty of 35–60 kg ha^{-1} day^{-1} in wheat in Indo-Gangetic plains (Pathak et al. 2003). Significant advancement of wheat sowing by 7–10 days in Haryana and by 8–25 days in Bihar, with zero tillage with residue retention technology was reported by several workers (Malik et al. 2002a, b). Scarce renewable resources such as diesel fuel saved in the tune of 15–60 l/ha owing to a 60–90% fuel saving (Malik et al. 2002b; Laxmi et al. 2007b). Dhiman et al. (2003) has reported a 1–15% and 9–36% yield benefits in north western India and eastern India respectively with complete conservation agriculture-based systems. With the complete adoption of conservation agriculture-based crop establishment, wheat yield may be increased to a considerable extent in a sustainable manner so that natural resource base may be conserved. In terms of farm profitability, only adoption of zero tillage over conventional has yielded an extra profit of Rs. 3400–4800 ha^{-1} (Laxmi et al. 2007a). Higher cost savings and better yield returns with higher benefit cost ratio were reported from eastern Uttar Pradesh (Malik et al. 2002b).

13.4.2.2 Nutrient Management

Nutrients availability to the crops is one of the prime deciding factors for the realization of yield. However, in most of the places on earth, inherent soil fertility is unable to sustain intensive agriculture on it. Improvement and maintenance of soil fertility status through supplemental nutrient management is much needed (Graham et al. 2007). It has been estimated that about 50% of the total global agricultural production may be attributed to only the use of fertilizers in the system. And under today's challenging situation to keep a pace with the growing demand for agricultural produce, it has become more and more important to manage nutrient more efficiently. Under usage of the nutrients is unable to produce good yields and deplete the soil of many nutrients due to continuous mining. On the other hand, over-usage causes severe consequences such as toxicity, soil pollution, groundwater pollution with low nutrient use efficiency (Vitousek et al. 2009). Production of fertilizers itself is a sustainability barrier as it is a much energy-demanding process. Use of N, P and K was estimated to be at 162 mt in 2009 which sharply increased to 187 mt in 2015 and 199 mt in 2019. Such an increase is an indicator of production constraints to be soon revealed in the near future.

Balanced application of nutrients, primarily N, P and K, has been reported to have a positive impact over the yield sustainability of wheat (Shaharoona et al. 2008). Proper restoration of soil nutrient losses, in terms of crop removal and several losses, is of much importance for maintaining the soil productivity (Brummer et al. 2011). Best management practices for nutrients is to apply nutrients in proper time, at proper place, at proper rate and from proper source to synchronise with crop's demand for nutrient and minimize losses (Roberts 2007; Bruulsema et al. 2009). In general, the response of wheat to nitrogen or phosphorus is very striking to realize the yield benefit. Such responses are not much prominent for potassium (Vitousek et al. 2009; Colla et al. 2015). For such reasons, farmers generally apply nitrogen and phosphorus to wheat, completely avoiding the potassium. Several instances of nitrogen overdosing are also very common practice in the farming community.

To achieve higher nutrient use efficiency with optimum economic yield target, it is necessary to maintain the right balance and proportions of nutrients in the soil (Kumar et al. 2018). The nutrient placement also plays a very important role especially in the availability of less mobile nutrients like phosphorus in deficient conditions (Nkebiwe et al. 2016; de Willigen et al. 2018). Rice-wheat system is a cereal-based monoculture prevalent in Indo-Gangetic plains. Such system has become multi-nutrient deficient including N, P, K, S, Zn, B etc. due to neglected management of potassium, fewer and fewer addition of organic matter, switching to high analysis phosphatic fertilizer in place of sulphur-containing Single Super Phosphate etc. The Table 13.6 describes nutrient deficiency status reported from several on-farm experiments across the wheat growing region. Such inadequacy of nutrients across the whole Indo-Gangetic plains is a major limitation in achieving higher productivity of wheat.

Site-Specific Nutrient Management (SSNM) in wheat with aims of feeding the crop as and when it requires, may provide a way out from the vicious cycle of poor nutrient management, poor yield and low input use efficiency. Careful site-specific

Table 13.6 Multi-nutrient deficiency status of several wheat growing zones

Location	Deficient nutrient status								
	N	P	K	S	Zn	Fe	Mn	Cu	B
Modipuram	+	–	+	+	+	–	+	+	+
Pantnagar	+	+	+	–	+	–	+	–	+
Kanpur	+	+	+	+	+	–	–	–	–
Faizabad	+	+	+	+	+	–	+	–	+
Varanasi	+	+	+	+	+	–	+	+	+
Sabour	+	+	+	+	–	–	–	–	–
Ranchi	+	+	+	+	+	–	–	–	+
Palampur	+	+	+	+	+	–	–	–	+
Ludhiana	+	+	+	+	+	+	+	+	+
Jammu & Kashmir	+	+	+	+	+	–	+	+	–

Note: '+' sign indicates presence of deficiency and '–' sign indicates absence of deficiency of a particular nutrient

Adapted from Tiwari (2006) and Tiwari et al. (2006).

Table 13.7 Wheat yields under SSNM and state average yields

Location	Yield of wheat after rice		Increase in yield in SSNM (%)
	State average yield (kg ha^{-1})	SSNM based yield (kg ha^{-1})	
Jammu and Kashmir	1325	4746	258
Punjab	4532	6548	44
Uttar Pradesh East	2755	5940	116
Uttar Pradesh West	2755	5685	106
Jharkhand	2056	4057	97

Adapted from Sharma and Tiwari (2004).

management of nutrients may result in the realization of yield targets of wheat as shown by Sharma and Tiwari (2004) (Table 13.7).

IPNI and Project Directorate of Cropping System Research have also concluded the possibility of a several-fold increase in yield and possibility of achieving higher yield targets through integrated site-specific management of nutrients (Tiwari et al. 2006). For micro-nutrients and secondary nutrients, wheat has been reported to show variable responses across locations. Response to the application of S was ranged between 48–1350 kg kg^{-1}. However, average responses to Zn, B, Mn and Cu were in the tune of 313, 382, 231 and 173 kg kg^{-1} respectively (Sharma and Tiwari 2004). Biradar et al. (2006) from southern states had reported on an average 23% yield benefit over recommended dose and 39% yield benefit over farmers' practice which resulted in an additional farm income of Rs. 3060 and 4545 per hectare respectively. Similar findings were suggested by Maiti et al. (2006) from Eastern India using Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) approach and

SSNM. Real-time nitrogen management through precision management with SPAD, Leaf Colour Chart (LCC), Green Seeker etc. are also good options to increase the nutrient use efficiency. Use of nutrient experts, artificial neural network and online fertilizer recommendation based on satellite-based fertility maps are also gaining momentum for catering the time and space variability and disparity in the soil fertility.

13.4.2.3 Water Management

Wheat is a winter crop and largely grown under irrigated condition in India. In the post green revolution era in North-Western India, an unprecedented increase in the groundwater has been witnessed in the rice-wheat system. Such a higher level of groundwater use soon led to overexploitation of groundwater resources which is a challenge in ensuring the production sustainability (Rodell et al. 2009). Cheap electricity, subsidised fuel and pumps with an elevated response of rice and wheat to supplemental irrigation have made India the largest consumer of groundwater resources especially after the green revolution in the country (Mukherjee et al. 2015). India's groundwater consumption accounts for nearly 25% of the world's groundwater resources (Margat and Van der Gun 2013). Indiscriminate use and overexploitation of water resources soon resulted in the depletion of the groundwater table which is speculated to be at the fastest pace in the world (Aeschbach-Hertig and Gleeson 2012). In the post green revolution era, the groundwater table has fallen from 8 to 16 m below ground level in the Indo-Gangetic plains with the rice-wheat system. Such alarming conditions demand immediate actions for reducing water use and increase water productivity as well as water use efficiency.

Current water productivity of wheat ranges from 0.8 to 1.6 kg m^{-3} in India (Zwart et al. 2010; Meena et al. 2015). Further, the irrigation efficiency in India is on an average not more than 35% which is even lower than the South Asian average (Rosegrant 1997; Ali 2012). Precision management of irrigation water can ensure proper soil moisture to support higher yield as well as high water use efficiency in wheat (Meena et al. 2018). Excessive irrigation can cause waterlogging, soil salinization as well as the loss of available nutrients beyond the root zone. For such reasons, irrigation water should be in tune with plant needs, soil conditions and atmospheric variability to ensure higher water use efficiency (Qiu et al. 2008). Scheduling of irrigation at critical physiological stages, rather than applying tons of water flooding the field frequently, is considered to be superior. Several workers have even suggested that intentionally under irrigating the crop at certain stages with deficit irrigation may improve crop productivity as well as water use efficiency (Stockle and James 1989; Lobell and Ortiz-Monasterio 2006; Peake et al. 2014). Such options provide an opportunistic way where water is a limiting factor for crop production as well as conserving most scarce natural resource. Different simulation model-based studies suggest potentials of such deficit irrigation strategies in wheat (Panda et al. 2003; Jalota et al. 2006). Panda (2003) has also suggested that irrigating wheat at 45% depletion of available soil moisture may prove beneficial to achieve higher yield with higher water use efficiency. Recent developments in irrigation technologies show the potential of adopting micro-irrigation practices for wheat

(Ahmadi et al. 2010). With the use of a drip irrigation system, irrigation efficiency can be elevated to 70–90% from current 35% to 40% level due to reduction in evaporation, surface runoff and deep percolation losses (Postel 2000). Development of an optimum irrigation scheduling is thus of utmost importance for the sustainability of food grain production system.

Proper crop establishment technique can also be effective to save irrigation water in wheat. A saving of 20–35% water only in wheat crop grown under continuous zero tilled system with retention of surface residue was reported by Mehla et al. (2000). Such numbers can be translated in to about one million litres water saving per hectare per season. With conservation agriculture system, it is possible to use residual soil moisture in a better way and thus requirement of irrigation may further be reduced (Mehla et al. 2000; Laxmi et al. 2007a).

13.4.2.4 Weed Management

Weeds are one of the worst enemies of the crop as it alone contributes to one-third of the total crop losses due to all pests (Chhokar et al. 2012). Weeds cause a huge penalty in the rice-wheat system and pose a barrier to the realization of the genetic potential of crops (Harrington et al. 1992).

Strategic weed management in wheat starts with the adoption of preventive measures. Wheat seed contaminated with *Phalaris minor* poses a huge threat for increasing the weed pressure in farms. In a recent drill box survey for wheat, it has been found that nearly 89% of the drill boxes contained *P. minor* seeds admixture with wheat seeds (Chhokar et al. 2012). Use of quality seeds may reduce such incidence to a significant extend (Nichols et al. 2015). Adjustment in the time of sowing in a thoughtful manner can also reduce weed problems in wheat. For example, several studies have found that early sown wheat escapes the problem of *Phalaris* due to unfavourable temperature for the germination of *Phalaris* along with wheat (Chhokar et al. 1999). On the other hand, the problem of wild oat is more under early sown wheat (Malik and Singh 1995b). Area-specific weed flora may thus be judged and crop management can be changed accordingly. Crop rotation may also be an effective option to reduce the pressure of crop bound and crop associated weeds. Rotation of wheat with sunflower, berseem or sugarcane is effective to reduce the infestation of *Phalaris* than rice-wheat rotation. Malik and Singh (1995a) reported that isoproturon resistance in *Phalaris minor* was reduced to 16% in cotton-red gram-wheat rotation in comparison with 67% in rice-wheat system.

Mongia et al. (2005) had found that row spacing and crop geometry of wheat also influence the weed pressure. He had reported a 23% reduction in the weed density when wheat was sown in 15 cm row spacing in place of normal 22.5 cm row spacing. Varieties also vary in their competitiveness with wheat. Tall wheat varieties were more competitive to weeds than introduced high yielding dwarfs Challaiah et al. (1986). Careful breeding efforts may transfer weed competitiveness to today's high yielding varieties. Fertilization practice also shapes the weed flora in wheat. More and more use of nitrogenous fertilizers completely suppress leguminous weeds and shift the flora in favour of grassy weeds. Whereas, use of phosphatic fertilizer in proper doses maintains broadleaf weeds population and thus balances the weed flora and resist weed flora shift towards a few problematic and resistant weeds (Chhokar et al. 2012).

Stale seedbed technique, also known as Dab system, is another effective option to reduce weed pressure as well as the seed bank strength in the soil (Lee and Thierfelder 2017). In this system, weed germination is stimulated with the use of light irrigation after land preparation and the emerged weeds are then killed with non-inverting tillage or with non-selective herbicides. Such a system was found effective to reduce weed population in wheat but in the rice-wheat system, it causes a delay in the wheat sowing (Chhokar et al. 2007a).

Several workers had recognised tillage as a major factor for shaping the weed flora locally (Buhler 1995; Yenish et al. 1996). Tillage effects seed distribution of weeds in soil layers and thus affects seed bank dynamics (Dey et al. 2018). It had been found by Catizone et al. (1990) that reduced tillage in wheat favours *Convulvulus arvensis* and *Cirsium arvense* than *Phalaris minor*. Zero tillage often reduces *Phalaris* problem due to the lack of disturbance in soil (Chhokar et al. 2007b). Weeds may further be reduced under conservation agriculture with non-selective herbicides and residue retention in the surface (Franke et al. 2007). However, continuous practise of zero tillage without other weed control measures, weed flora may shift in favour of problematic broadleaf weeds like *Malva parviflora* and *Rumex dentatus* (Chhokar et al. 2007a). Anderson (2005) had reported that multiple successive no-till systems are effective in reducing weed seed bank by exposing them to vagaries of weather.

Mechanical and manual managements of weeds, though effective, are limited by feasibility, profitability and availability of manpower. Chemical control of wheat is the most popular among all the weed control measures due to its rapid action, easy application and cost-effectiveness. However, injudicious application of herbicide may pose serious problems like environmental pollution, drift hazard, weed flora shift and the emergence of herbicide-resistant weeds (Singh et al. 2004; Chhokar et al. 2007b). Herbicides must be used in right time and right dose to right place to get optimum result. Keeping today's problems in mind, herbicides must be applied in the recommended dose and preferably in combinations and mixtures to control complex weed flora as well as avoid problems emerging from herbicide use (Singh et al. 2011).

No single weed management practice is efficient against dynamic weed flora for a long time. For such reason, the integrated approach of weed management must be followed to combat the problem of weed for a long term in a sustainable manner.

13.4.2.5 Other Managements

Many other management factors are also there for improving wheat productivity, profitability and sustainability. Disease-pest management is one of the important aspects to remove yield limitations prevailing in some regions. Major diseases and pests are described in previous sections. An area-specific integrated approach must be adopted to keep the pest population below the economic threshold level. Such integration of different available means reduces the input costs as well as increases the efficiency of the management practices. Use of quality seed, free from disease-pest inoculum and development of resistant varieties are some of the best measures to cut down the probabilities of crop damage by the disease-pest infestation.

Sustenance of the production under the changing climatic scenario is a real challenge today. Use of varieties that are better adapted to aberrant weather conditions may be a way to maintain the production even under challenging climatic conditions. Besides, adjustment of sowing time, use of conservation agriculture practices, proper nutrient management, use of soil cover, seed priming are some technologies known to improve the performance of wheat under changing climatic conditions.

13.5 Integrated Crop Management for Wheat

Wheat is grown under diverse agro-climatic conditions across India. With each different region of wheat cultivation, there comes different opportunities and threats (Bhatt et al. 2016). For example, North-Western plain zone (NWPZ) is the traditional wheat-growing zone and blessed with the highest productivity of wheat in the country. But, after the green revolution several problems such as decreasing factor productivity, degradation of natural resource, increase in the input cost, yield stagnation etc. came into the picture (Bhatt et al. 2016). Built-up of rust, resistant *Phalaris minor*, groundwater pollution, residue burning are other issues to be addressed in NWPZ (Ramadas et al. 2019). In North-Eastern Plain Zone (NEPZ), the problems are quite contrasting from NWPZ. Small land holding, lack of irrigation facility, poor fertilization, low level of farm mechanization, shorter growing period, terminal heat stress are prime issues to be considered. NEPZ contributes to the second largest wheat producing area in the country. But the productivity of wheat is quite low from the varietal potential and even from the productivity of NWPZ (Tripathi and Kumar 2010). Such a condition shows a path for the wide scope of achieving higher yields in this region as yield stagnation and saturation is yet not an issue. Development of infrastructure to ensure better availability of inputs like quality seed, fertilizer, chemicals at the proper time with careful integrated agronomic management can really bring a second green revolution especially in eastern India (Pingali 2012; Ariga et al. 2019). Lack of information, damages from bird and wild animals, adoption of newly released high yielding and resistant varieties, proper pest management, scarce availability of machinery with lack of irrigation water still remain major production constraints in North Hill Zone (NHZ) and Central Zone (CZ). Specific issues of each wheat growing zones are unique to the situation and thus be handled separately. Zone wise proper management plans will cater yield variability to a great extent and thus may increase national production and productivity sustainably (Ramadas et al. 2019).

13.6 Conclusion

Wheat production can largely be considered as a basic pillar in the maintenance of the country's food security. India has improved its wheat production many folds from the pre-green revolution era to present the scenario. However, further increment in the production and productivity to keep pace with the bulging population has been challenged by several factors. Recognition of the existence of a technology gap is the basic step to solve any technology-related problems. Challenging issues in wheat production in the country has now been well addressed and discussed in various forums. Which is of utmost necessitate for the generation of new technology intervention and create public information base. Area and locality specific integrated approaches are most desired in today's context to address the variability. Even, whenever feasibility exists, advantages of niche area based site-specific management down to the single domain level must be adopted. Countrywide such initiatives must be made to ensure a food secure future and side by side, conservation of natural resources future must be given due consideration for the sustainability of such a food secure future of the country as well as the world.

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Improved Agronomic Practices for Enhancing the Resource Use Efficiency and Productivity of Wheat and Barley

14

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14.1 Introduction

Wheat and barley are two important winter season cereal crops cultivated worldwide. Wheat occupies maximum area among all the crops grown globally due to its better adaptation and preference as staple food, feed and fodder crop. Wheat besides a main source of starch and energy, also substantially provides other numerous beneficial components such as protein, vitamins (particularly B vitamins), dietary fiber, and phytochemicals (Shewry and Hey 2015). In India also, wheat being the prime staple food is cultivated over an area of about 30.55 m ha area with a productivity of about 3.51 t/ha and production of 107.6 mt. (DES 2021). It contributes about 37.1 per cent of the food demand in India. The barley area in India is about 2.03% of the wheat. The differences in support price and yield potential of wheat and barley influenced the acreage under these two crops. The barley is preferred over wheat in area having salinity problem and poor irrigation facilities because of its better tolerance to these abiotic stresses (Mass 1986).

The improved varieties, increased irrigation, better mechanization, fertilizer usage and increased area have contributed in boosting the production and productivity of wheat crop. However, to meet the food demand of burgeoning population from same or even from lesser land resources due to allocation of cultivable land to other sectors, production and productivity of wheat and other crops need to be increased in a sustainable manner.

In the present scenario, the yield stagnations are being observed in major wheat and barley growing areas (Brisson et al. 2010; Ray et al. 2012; Schauberger et al. 2018). The major reasons for yield stagnation consist of soil health deterioration (degradation of the soil structure, increased salinization and alkalinity, multiple

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nutrient deficiencies/nutrient imbalances, formation of the hardpan; low soil organic matter contents; monocropping pattern, water scarcity and emergence of problematic weeds, insects and diseases. Concerns have been expressed on practicing the intensive tillage again and again, which is associated with degradation of soil structure, soil compaction and soil health. It leads to depletion of soil organic carbon, decreasing soil fertility and reduced factor productivity (Yadav 1998). The injudicious use of irrigation water, fertilizers and chemicals has also led to soil fertility loss in addition to depletion of ground water and soil and underground water pollution (Nayar and Gill 1994). The evolution of herbicide resistance (Chhokar et al. 2012) in weeds is going to be a serious threat to wheat and barley production in the years ahead. Therefore, to achieve the sustainable higher wheat and barley productivity as well as profitability, efforts must be focused on reversing the trend in natural resource degradation by adopting the efficient resource conservation technologies.

In this chapter an attempt is being made to discuss the various improved agronomic practices and their influence on crop productivity and natural resources.

14.2 Suitable Cultivar Selection

Selection of suitable latest high yielding variety specific to different growing conditions (viz. timely, late sown, irrigated, rainfed and salinity-alkalinity) is a pre-requisite for realization of high productivity. Before green revolution, tall wheat varieties were grown, which were having tendency to lodge under heavy fertilization and irrigation but in post green revolution era, short statured varieties responsive to irrigation and fertilization significantly improved the production and productivity. Thus green revolution witnessed with the introduction of dwarf, input responsive and photo insensitive varieties. Similarly, traditional grown barley varieties were tall and weak stemmed and generally lodged even under relatively low soil fertility conditions and these were replaced with high yielding dwarf and input responsive varieties. These varieties were quickly adopted on large scale by the farmers.

Crop cultivars blending is another tactic that can be used as a measure for improving the grain yield stability and quality as well as disease control (Cowger and Weisz 2008; Faraji 2011; Creissen et al. 2016). In variety mixtures/blending, two or more component varieties are grown simultaneously within the same field, thus providing the crop stand diversity. The hypothesis is that genetic, physiological, structural and phenological diversity among component varieties may drive beneficial interactions between varieties and between varieties and environments (Kiær et al. 2009). The yield advantage is mostly under some adverse conditions (frost damage, heat stress, moisture stress, erratic rainfall, insect-pest incidence). Bowden et al. (2001) reported that while mixing care should be taken to blend the high yielding varieties having diverse genetic background and weakness of one should be compensated by other. Creissen et al. (2016) reported that barley variety mixtures were less diseased, less prone to lodging and had stable yields than monocultures. The compensation is the major ecological process contributing to yield stability in diverse cultivar mixtures (Wolfe 1985; Smithson and Lenne 1996; Mundt 2002; Cowger and Weisz 2008), where one component cultivar affected by biotic or abiotic stress is compensated by improved growth of other component cultivar. The other mechanism that may give yield advantages is complementary patterns of canopy or root architecture, leading to efficient utilization of light, moisture and nutrients (Trenbath 1974; Smithson and Lenne 1996; Essah and Stoskopf 2002). The blending yield advantage in small grains is larger with having more than two components (Nitzsche and Hesselbach 1983; Stuke and Fehrmann 1987; Newton et al. 1997). Similarly, Nitzsche and Hesselbach (1983) studied blends of spring barley and reported that yield increased as the number of components in the blends increased from two to six.

Exploitation of hybrid wheat and barley is another option of realizing yield gain. Mette et al. (2015) reported that opportunity exists of yield increase with hybrid wheat. Mühleisen et al. (2014) also evaluated the grain yield stability in wheat, triticale, and barley hybrids in comparison to lines and observed higher yield stability for hybrids in all these three autogamous crops. Hybrids can also offer better tolerance to abiotic stresses (Mette et al. 2015). Exploring such horizons can give a boost in the global wheat and barley production.

14.3 Sowing Time and Method

The appropriate sowing time and method are the key factors to harness the maximum crop yields. The sowing time should be adjusted to have favourable conditions for tillering and grain filling period so as to exploit the maximum productivity. In Indian conditions, the optimum sowing time for wheat and barley is the first fortnight of November (Coventry et al. 2011; Chhokar et al. 2017; Sharma et al. 2020). However, sowing time depends on the preceding crop to wheat, grown in wheat based cropping system. Generally, wheat sowing is delayed when sown after cotton, basmati rice, sugarcane and some vegetable crops in rotations. Delay in sowing of wheat causes marked reduction in grain production mainly due to reduced tillering and reduced number and weight of grains per ear (Singh et al. 1989). Under such situations, some of the practices like zero tillage seeding, relay cropping, seed priming and growing short duration varieties can be helpful (Chhokar et al. 2017; Sharma et al. 2020). The surface seeding can also be an option in conditions, where soil remains wet for longer period particularly under rice fallows in eastern India. This technology besides advancing the sowing time also increases the cropping intensity (Sharma et al. 2020).

In light soils, dry seeding followed by irrigation can be adopted to avoid delay in sowing and providing better crop emergence. Another agronomic intervention for delayed sowing in wheat and barley is to increase the seed rate by 25% (125 kg/ha) along with closer row spacing (15–18 cm) for better yields.

Optimum planting geometry (plant population and their distribution) can be achieved through seed rate and spacing adjustments to realize the full genetic potential of a variety. It should be like that it minimizes the intra-plant competition and maximizes resource utilization (space, solar radiation, nutrient and moisture) for higher yield. So, the plants should be equidistantly arranged from each other in the field to equally share the growth resources (Berry 1967). Many researchers reported the wheat yield gain with cross sowing as compared to unidirectional line sowing (Dhiman et al. 1984; Jadho and Nalamwar 1993; Chhokar et al. 2017). Whereas, compared to farmer practice of broadcast sowing, both line and cross sowings provided better crop yield (Arif et al. 1997; Dhiman et al. 1984). Closer or cross sowing of wheat was also found effective in reducing the weed problem due to limited availability of space to weed populations (Jadho and Nalamwar 1993; Solie et al. 1991; Teich et al. 1993). Thus, crop yield can be enhanced through right choice of cultivar, seed rate, spacing and crop establishment methods.

Seed priming is another agronomic intervention for improving the seed germination under unfavorable soil moisture conditions. Under moisture stress conditions, sowing of primed seeds can provide the higher productivity of wheat and barley. Harris (1996) and Hamdollah (2013) shown that just soaking seeds in water before sowing increased the speed of germination and emergence, leading to vigorous seedlings and better crop stands. Similarly, improved crop establishment and wheat productivity have been reported with hydropriming and osmopriming (Farooq et al. 2008). So, this practice can be utilized for improving crop establishment under limited soil moisture or delayed sowing conditions.

14.4 Conservation Tillage Technologies

14.4.1 Laser Land Leveling (LLL)

Laser land leveler is an important resource conservation technology. Generally, agricultural fields are not precisely levelled, which leads to poor performance of crops. Such performance of crop is associated with the fact that part of the field area at higher elevations suffers from water stress while part of area with lower elevations experience surplus water condition causing variability in water and nutrients applied to crop. Laser land leveling is a pre-requisite for enhancing the benefits of other conservation technologies. Laser land leveler consists of scrapper, hydraulic system, transmitter, receiver and control box as main components (Jat et al. 2006, 2014; Singh et al. 2020). Laser land leveler precisely levels the field within ±2 cm of mean elevation of the field by scrapping the soil from higher elevations and spreading it over lower elevation zones. Laser land leveling improves the use efficiency of water and other agricultural inputs such as fertilizer, pesticides, herbicides, etc. This technology also increases the cropping area by 3–5% due to reduction in area covered under bunds and channels, thereby enhancing the crop yield along with better utilization of available resources. In laser leveled fields, the yield advantage of 10–20% has been observed in wheat-based cropping systems due to uniform water distribution, proper crop stand and growth, uniform maturity, higher input use efficiency and increase in cultivable area (Jat et al. 2006; Kaur et al. 2012). Laser land leveling technique reduces the irrigation water requirement by 20–30% while improving NPK uptake efficiency by 27–64% due to higher and uniform application efficiency of inputs. It also reduces the irrigation application time, labour cost, and can save up to 750 kWh annual electricity for one hectare area under rice-wheat system (Jat et al. 2006, 2009, 2014; Latif et al. 2013; Aryal et al. 2015). The benefits are also extended to environment due to reduction in associated harmful air pollutants, where diesel engines are used for irrigation purpose.

14.4.2 Zero Tillage (ZT) Technology

This is a resource conservation technology in which wheat or other crops are directly seeded into undisturbed soil after harvesting of rice or other crops using a specially designed machine called zero-till ferti-seed drill. Under this practice, seed and fertiliser are placed into narrow slits created by furrow openers (usually inverted-T type) of zero-till ferti-seed drill. The ZT seeding is mainly adopted for wheat under rice-wheat system in India. Various researcher have shown that ZT technology provides similar or higher wheat yield over conventional tillage (CT) practices (Erenstein and Laxmi 2008; Keil et al. 2020). The benefits of higher grain yield with ZT technology are also extended to barley crop (Singh et al. 2013). However, ZT provides yield advantage in the regions where sowing is delayed under CT system, which can be advanced by adopting this technology.

The main drive factor for adoption of ZT technology in high yielding and more mechanized regions of north western India and Pakistan was to reduce the cost of field preparation, where huge amount of money and time were being invested for field operation. This technology reduced the cost of wheat sowing by 87-89% (Sharma et al. 2004c, 2005). Moreover, total energy required also reduced significantly from 23,631 MJ ha^{-1} for broadcast sown wheat to 20,279 MJ ha^{-1} for wheat sown ZT practice. The benefit-cost ratio was also maximum for ZT wheat while it was the lowest for broadcast sown wheat. A reverse trend was observed for specific energy (energy spent per kg of biomass production) requirement being lowest for ZT wheat and highest for broadcast sown wheat after conventional field preparation (Sharma et al. 2004c). At present, ZT can reduce the cost of cultivation by more than Rs. 3000 per hectare, thereby increasing net profit to the farmers. Other benefits of this technology are reduced soil erosion, lesser compaction at soil subsurface, lesser harmful air pollutants from agricultural fields, lower incidence of termite (Sharma et al. 2004b), lesser chances of Karnal bunt (Sharma et al. 2007) and irrigation water saving (about 3%) over conventional tillage. The development of resistance against commonly used herbicide 'isoproturon' in *Phalaris minor* in India was also responsible for accelerating the adoption of ZT in rice-wheat system due to lower incidence of this weed under ZT practice (Sharma et al. 2004b; Chhokar et al. 2007). The less weed problem under ZT was probably due to less soil disturbance helps in keeping the weed seeds at depth from where it could not germinate. This technology also provides other benefits such as up to 92% saving in diesel, reduced irrigation water in first irrigation, advancing the wheat sowing (4–5 days) and lesser infestation of *Phalaris minor* over conventional practice (Sharma et al. 2005, 2018). If diesel

Table 14.1 Arable land and zero-tillage area in selected countries

Country	Zero-tillage area (m ha)	Arable land area (m ha)	% of arable land area under ZT practice
Australia	13.78	30.06	45.83
Denmark	0.03	1.83	1.75
France	0.53	14.65	3.61
Germany	0.09	8.66	1.08
India	2.20	156.46	1.41
Netherlands	0.01	0.78	1.03
USA	42.27	145.02	29.15

Source: FAOSTAT; Sepat et al. (2013); DES (2019)

saving under ZT practice is extended to larger area, a huge savings can be realized annually. Moreover, it provides a healthy environment by reducing the green house gas emissions, which is one of the major factors responsible for global warming. Despite all these multidimensional benefits, overall adoption rate of this technology in India is very low as compared to developed countries like USA and Australia as presented in Table 14.1. It requires further systematic efforts in research and development and more trainings and field demonstrations for escalating the adoption of ZT technology among farmers belonging to small land holdings and engaged in cropping patterns other than rice-wheat.

14.4.3 Reduced/Minimum Tillage Technology

The benefits of ZT brought the significant changes among the farmers to shift from intensive tillage (involving 6-17 field operations for seed bed preparation) to reduced tillage (2-3 field operations) involving various farm implements (Sharma et al. 2005). The reduced tillage option also reduces the tillage cost. Reduced tillage may be advantageous over ZT under specific conditions such as it controls the weeds germinated after harvest of the previous crop, provides better efficacy of pre-emergence herbicide and levels the field after the formation of tracks during the combine harvesting under moist soil conditions. If certain problem exists then strategic tillage can be employed.

14.4.4 Rotary Tillage/Super Seeder Technology

Rotary tillage is alternate to intensive tillage practice, which provides seed-bed condition similar to intensive tillage but with reduced energy, time and drudgery. It has been widely adopted by the farmers of north-western IGP regions. Rotavator is a good example of rotary tillage implements. Rather than going for individual operation of preparing the seed-bed with rotavator and then sowing with drill, rotary-till-drill or super seeder provides the opportunity to complete these operations in one go. This machine is a combination of rotavator and seed drill, where front unit prepares the seed-bed and then sowing operation is performed by seeding attachment at back of the machine in a single pass. This machine has seven flanges with six blades (L or LJF type) mounted on each flange. It allows mixing of anchored and loose rice residue (medium to heavy load), weeds and green manure crops with soil followed by simultaneous seeding operation. In simultaneous completion of seed-bed preparation and seeding operations, soil moisture is conserved, which leads to better crop stand in addition to savings on energy, time and labour requirement making this technology more economical and eco-friendly. The power requirement of machine is comparatively high over similar size strip-till drill as it provides complete coverage of soil. A super seeder with 2.2 m working width requires at least 60 hp. tractor for its effective working under medium to heavy residue conditions. The adoption of rotary tillage technology saves energy and time along with 7–10% higher yield over conventional sowing practice (Sharma et al. 2002; Chauhan et al. 2003; Sharma et al. 2018). Moreover, it helps in advancing the sowing of wheat, which is generally delayed under conventional sowing practice after harvesting of rice. It also provides improved germination of seeds as soil is pulverized with good tilth quality prior to placing of seed and fertilizer into soil. The easy detachment of seeding unit from rotary till drill also allows its use for puddling as rotary tillage provides excellent quality of puddling. A single operation after ponding of water is sufficient for puddling depending upon soil type. The large-scale adoption of such multipurpose machines can save fuel, labour cost and time along with timely sowing of crop and better crop productivity.

14.4.5 Strip Tillage Technology/Strip-Till Drill

It is another resource conservation machine, which uses rotary action for minimum manipulation of soil with the help of J/C-type blades mounted on flanges. The structure and power transmission of machine is similar to rotavator except type of blades used. The blades (J/C-type) mounted on flange prepares a narrow strip (60–80 mm) rather than complete coverage of soil, which reduces the volume handled by the machine per cycle and saves energy over similar sized rotavator or Super seeder. It may also have the provision of seed and fertilizer drilling and referred as strip-till drill, where a narrow strip of soil is prepared in front of every furrow opener prior to seeding operation. It provides an intermediate option between conventional and zero tillage with lesser tillage cost but with crop stands similar to conventional practice of sowing. Strip-till conserves energy and resources while reducing the input cost due to partial tillage action. It also reduces the soil erosion because undisturbed soil is left with crop residue cover throughout the year. It provides better seed-soil contact leading to higher germination and crop stand over ZT practice particularly in summer months. Strip-till drill with nine flanges provides field capacity of 0.25–0.40 ha h^{-1} while saving 50–60% diesel over conventional method.

14.4.6 Raised Bed Planting Technology/FIRBS Technology

In this conservation technology, bed formation, placement of fertilizer and sowing of wheat or other crop is done in a single operation after land preparation. The beds can be narrow or broad. The most common configuration of beds for wheat and barley is 67.5 cm, which consists of 37.5-cm wide bed top and 30- cm wide furrows and it is known as Furrow Irrigated Raised Bed System (FIRBS). The bed planting machine makes two beds in one go and 2–3 rows of wheat and barley are sown on each bed. It is quite useful in light textured soils having limited water availability as well as in alkali soils having problem of water stagnation. It also allows placement of fertilizer even in the standing crop of wheat or barley. This technology saves 30–40% water and 25% of seed and nitrogen without any yield penalty in wheat crop depending upon the soil type. Sharma et al. (2005) reported the irrigation water saving more than 30 per cent in case of bed planted wheat cultivation. Crop cultivars having high tillering are more suited under raised beds cultivation practice. This method of wheat cultivation is also suitable for seed growers due to enhanced size of grains and easiness in rouging operations. It reduces the dependency on herbicide due to possibility of mechanical weeding and simultaneous placement of fertiliser by bed planter fitted with inter culture tines. In situations, where sowing is likely to be delayed due to pre-sowing irrigation, dry seeding can be done on raised beds followed by irrigation immediately after seeding. In this practice, irrigation can also be given at grain filling stage, which is generally avoided by the farmers under flat planting due to chances of crop lodging pertaining to higher biomass and wind velocity at that time. However, greater incidences of powdery mildew (Sharma et al. 2004a) and termite (Sharma et al. 2004b) problems have been observed in wheat grown on beds. Bed planting method also reduces the chances of *Phalaris minor* germination and its infestation on the top of beds due to faster drying and lesser moisture availability.

In other than rice-wheat system, permanent raised bed (PRB) planting system can help in savings on cost, energy, drudgery and time due to elimination of field preparation prior to sowing of crops. With proper selection of crops and their cultivars, this technology can help in improving the system productivity and water use efficiency (WUE) or water productivity (WP). It has been observed that bed planting method gives significant higher yield in water sensitive crops like oilseeds and pulses. Sayre (2004) found that wheat and maize planted on raised beds provided 29% saving in irrigation water over flatbed planting method in Asian countries. Govaerts et al. (2005) reported lesser cultivation costs and higher sustainability of maize-wheat system with PRB technique over flat planting method. This planting method also lowers seed rate requirement than that of flatbed planting method for a similar yield and reduces the lodging of crops. Similarly, Jat et al. (2013) reported that both PRB and ZT flatbed systems were superior in terms of yield, WP, profitability and soil physical conditions than conventional flatbed method in maize-wheat cropping system. Akbar et al. (2007) reported that farmers using PRB system saved about 36% water in wide beds (130 cm) and 10% water in narrow beds (65 cm) along with about 6% and 33% improvement in yield of wheat and maize crop, respectively.

In bed planting system, crop residue can be retained on soil surface to avail the benefit of conservation agriculture (CA). Such planting methods also allow the possibility of intercropping or relay cropping, which can increase the system productivity and profitability (Sayre and Moreno Ramos 1997). For instant, sugarcane can be intercropped or cucurbits can be planted in furrows of bed planted wheat. Possibility of growing other crops on beds after wheat, without tillage operation was seen as a way for reducing the number of tillage operations and lowering associated cost and harmful emissions, thereby reducing the cost of cultivation in an economically-sound manner. Under FIRB technology, many crops like maize, soybean and pigeon pea in *Kharif* and vegetable pea and mustard in *Rabi* season can be grown as per recommended practices. Generally, these crops are sensitive to water logging and prone to lodging. This technology provides an opportunity to grow these crops with less risk of water logging and lodging. Probably, these benefits lead to higher crop yield and better net-profit to farmers.

A cultivation system reverse to raised bed planting i.e. ridge-furrow combination (e.g. 30 cm wide each and 15 cm high ridges) can be very successful for rainwater harvesting to achieve higher yield and WP in maize and wheat crops (Li et al. 2016). In this cultivation system, crop is planted in the furrows rather than on raised beds which helps to harvest more water in the furrows from limited rainfall and to reduce the runoff during heavy rainfall events. In this cultivation method, surface mulching (plastic film or crop residues) can be kept on the ridges to reduce the evaporation losses and weed problems. This cultivation system is useful in arid and semi-arid regions, where plants usually experience water stress conditions.

14.4.7 Surface Seeding

This practice does not require any field preparation and seeding is done after crop harvesting or in standing crop, a few days before harvesting operation. In some rice areas under eastern IGP, land remains wet for a long time after harvesting of rice, which does not allow field preparation for sowing of next crop. Under such situations, surface seeding provides an opportunity to take the wheat crop and enhances the cropping intensity by 100% i.e. converting the single cropped areas into double cropped areas. Even in areas, where field preparation is possible, wheat sowing is delayed leading to very low productivity. Hence, by adopting the surface seeding, one can harvest higher yields. In this technology dry or soaked seed is broadcasted over the wet soil. To prevent the bird damage, the seed is invariably coated with cow dung. For proper and uniform crop stand, drum seeders can also be used after harvesting of crops. Nowadays, this technology is not limited to wheat but also for other upland crops like pea, gram, lentil, etc. on farmers' field.

14.5 Crop Residue Management

Globally, huge amount of crop residue is produced every year in which India contributes about 685 million tonnes (Hiloidhari et al. 2014). Cereal crops predominantly contribute in total crop residue production with a share of 54%. Rice and wheat are major crops in cereal, contributing about 154 mt and 131 mt, respectively in residue production. In wheat based cropping systems, management of rice and sugarcane straw is a major problem for farmers especially in Indo-Gangetic plains (IGP). The residues of these crops have poor feed quality and farmers opt injudicious practice of residue burning as a quick and economical way of residue management for timely sowing of wheat crop. The other reasons like high labour cost in manual handling of residue, expensive residue handling machines and timely unavailability of such machines on hiring service encourage the farmers for residue burning practice. In critical window period between rice harvesting and wheat sowing, it is not possible for the farmers to incorporate the crop residue in soil using various tillage implements or to remove it from field for composting purpose prior to sowing operation. Therefore, considering yield aspect and above mentioned challenges, farmers adopt burning of rice residue and sugarcane straw for clearing the field and timely sowing of wheat crop. The burning of crop residue causes loss of precious nutrients retained in plants, deterioration of soil health (loss of valuable soil organic carbon, soil biota etc.) and conversion of various elements to harmful air pollutants causing global warming and human health deterioration. The proper management and utilization of crop residue in soil can keep continuing the hidden essential services of our ecosystem and building a sustainable natural resource base. In areas, where combine harvesting is practised, a huge amount of crop residue is left on the field, which can be recycled for nutrient supply rather than burning. About 25% of nitrogen and phosphorus, 50% of sulphur and 75% of potassium uptake by cereal crops is retained in crop residue. Burning of crop residues depletes 80–90% N, 25% of P, 20% of K and 50% of S present in them also besides increasing air pollution (Jain et al. 2019).

Crop residue can be managed by various in-field and off-field options. In-field management of crop residue is of prior interest, which utilizes the nutrients retained in residue and improves the soil quality. Like in off-field management of crop residue for industrial, energy and agricultural applications, there is no need of collection and transportation of residue under in-situ residue management practices. In in-situ options, retention of crop residue on soil surface seems to be a better option than incorporation as it reduces evaporation losses and soil erosion, avoids short-term nutrient tie up, and suppresses the growth of weeds. Moreover, slower decomposition rate of residue under surface retention practice over incorporation helps in building up soil organic carbon (Hooker et al. 1982; Havlin et al. 1990; Wood et al. 1990; Unger 1991). The practice of residue incorporation also requires complete coverage of soil by seedbed preparation unit of machine for effective mixing of crop residue into soil, which results in higher energy consumption over residue retention method. Contrary, residue retention method allows direct seeding of crops with minimum soil disturbance, leaving 60-75% area as undisturbed and covered with crop residue. In certain conditions, where seeding cannot be undertaken in the presence of surface retained residue then alternative is residue incorporation. Residue incorporation into soil has several benefits, such as, better soil structure, infiltration and soil porosity; in addition, it reduces soil bulk density and formation of hardpan and improve the soil quality index (Choudhary et al. 2018). Crop residue and tillage practices also influence the weed germination and establishment. Tillage is mainly practiced to prepare the seedbed and to control the weeds, which has been already germinated. But it is also responsible for distribution of weed seed bank, stimulation of the weed germination and emergence of many weeds through brief exposure to light (Ballard et al. 1992). Crop residues may influence the weed seed reserve in the soil directly or indirectly, weed germination and establishment and efficacy of soil-applied herbicides (Crutchfield et al. 1986). However, such effects depend on residue type, condition and residue load. Eguchi and Hirano (1971) observed that rice straw mulch reduced the weed density (*Polygonum lapathifolium*) in wheat. In other studies, Teasdale (1998) and Liebman and Mohler (2001) reported that surface retention of residue in combination with no-till system significantly suppressed the weed growth. No-till system reduces the weed emergence by lowering the exposer of weeds to light and by imposing mechanical impedance to weed seeds. In addition to act as mulch, residue retention moderates the soil temperature and soil moisture, which have direct effect on weed germination depending upon the type of weed flora, soil conditions, crop residue type and load. At lower residue level, the weed flora may be higher than the residue free conditions but at higher level, weed will be considerably reduced (Chhokar et al. 2009).

In the combine harvesting area presence of loose residue causes frequent clogging of furrow openers and interruption in seeding operation with normal seed drill, which forces the farmers to adopt injudicious practice of residue burning. However the use of conservation machines can resolve this problem..

14.6 Conservation Agriculture and Resource Use Efficiency

Conservation agriculture has three components viz. minimum soil disturbance, residue retention/soil cover ($\geq$30%) and crop rotation (FAO 2021a). It has huge potential of utilizing the crop residue within field. The adoption of CA principles results in numerous favourable outcomes. The minimum soil disturbance component improves the soil physical structure and soil biota. Crop residue retention as permanent soil covers protects the soil from water and wind erosion, increases water infiltration, reduces evaporation and water runoff, thereby provides better soil fertility and productivity (Thierfelder and Wall 2009). Surface residue retention also moderates the soil temperature and increases soil organic carbon in the upper soil layers. The third important principle of CA is crop rotation. The inclusion of legumes in rotation as sole or intercrop improves soil fertility with BNF (biological nitrogen fixation) and yield of succeeding cereal crop. Crop rotation and cover crops besides helping in recycling of nutrients also break the buildup of weeds, insects and diseases infestations, which under mono-cropping system adversely affects the plant health and crop yields (Giller 2001).

CA also helps in improving the nutrient use efficiency through reduced nutrient loss due to lesser runoff and soil erosion as well as bringing back the leached nutrients to topsoil through deep rooted crops in rotation (FAO 2021b). Thus, CA principles provide greater nutrients availability to the crops. Initially there may be immobilization problem due to presence of residue but over the time the nutrients mobilization from crop residue increases due to improved microbial activity (Carpenter-Boggs et al. 2003; Choudhary et al. 2018). Long term adoption of CA also increases organic matter and aggregates of top soil surface leading to increased nutrients as well as water availability (Franzluebbers 2002; Sharma et al. 2018).

Legumes are component of crop rotation in CA and leads to healthy soil conditions. The quantity of N fixed by legume varies depending on the nature of the crop. Burle et al. (1997) reported the highest levels of exchangeable K, calcium (Ca), and magnesium (Mg) in systems with pigeon pea and lablab (*Dolichos lablab*) and lowest in systems including clover. In rainfed conditions of Mexico with permanent raised bed planting system, Govaerts et al. (2007) reported higher C, N, K, and lower sodium (Na) with residue retention as compared to residue removal conditions.

The adoption of CA also helps in advancing the wheat sowing by 5–7 days in north western plains and may be much higher in the eastern India depending on the soil conditions (Sharma et al. 2005; Singh et al. 2020). This advancement of sowing helps in yield gain. Moreover, also provides huge fuel saving (about 80–90%). The cost saving and better or comparable yields of ZT over CT provide more profit margins (Chauhan et al. 2003; Sharma et al. 2018; Singh et al. 2020).

The adoption of CA practices can improve or sustain the wheat yield along with conservation of natural resource base even under unfavourable conditions. A global meta-analysis of the effect of CA practices showed worldwide average 2.5% crop yield reductions with CA (NT + residue retention+crop diversification) and reductions were more when CA component were partially adopted (Pittelkow et al. 2015). Also, the yield declines tended to decrease with increased period of CA adoption. However, yield gains of 7.3% were observed under rainfed agriculture. Under Indian conditions, the long term effect of CA has been found to improve the physio-chemical and biological properties of soil); water and nutrient use efficiency along with system productivity and profitability (Parihar et al. 2018; Sharma et al. 2018; Singh et al. 2020).

In a long-term field trial involving tillage, fertilization and grazing observed higher organic matter content, total N and aggregate stability but lower bulk density in NT systems compared with mouldboard plough. Usage of conservation tillage systems, besides contributing to soil health preservation also enhanced the crop production (Gil et al. 2009).

The retention or incorporation of crop residues may improve the phosphorus availability in soil depending on the quantity and P concentration of the crop residue (Damon et al. 2014). They further reported that inclusion of vigorous green manure crop releases significant amount of P to meet the subsequent crop requirements rather than a cereal crop residue. Further, nutrient availability from crop residue may also vary depending on the tillage and may be better with no-till option.

Recent efforts have been focused on direct seeding of crops while retaining the crop residue on soil surface. The retention of crop residue on soil surface provides the following multiple advantages (Mandal et al. 2004; Sharma et al. 2020; Singh et al. 2020), which are listed below:

- Conserves the soil moisture through reduced soil evaporation.
- Increased water infiltration and reduced runoff.
- Reduced soil and water erosion.
- Reduces weed infestation.
- Moderates soil temperature, lowers leaf canopy temperature at grain filling stage thus mitigates terminal heat stress in wheat.
- Less ground water pollution.
- Reduces GHGs emission equivalent nearly 13 tonnes/ha.
- Less flooding and low impact of unfavourable climatic conditions on crop.
- Increases soil biota.
- Slow decomposition helps in building up soil organic carbon and improves soil productivity and sustainability in long-term.
- More profitability due to reduction in cost, labour, time and energy requirement.
- Lesser soil compaction at subsurface layers and improved soil fertility.
- Lesser annual lube oil requirement, maintenance cost and wearing rate of moving parts due to reduced number of passes of tractor and elimination of tilling operations.

It has been observed that in long-term, CA increases the profitability by stabilizing and enhancing the crop yield, reducing the labour cost and overall cost in crop production (Kassam et al. 2009; Johansen et al. 2012), and by enabling for timely sowing of crops (Kassam et al. 2009; Ward et al. 2018; Singh et al. 2020). Based on several studies, a monetary gain of about $ 100 per ha can be achieved in wheat crop sown under CA practice (Keil et al. 2015). It also provides increased resilience to various climatic stresses (drought, excess water, cold and high temperature) and climate change adaptation and mitigation. Despite multiple benefits with CA, its adoption has been very slow especially in India due to lack of suitable CA machines, higher cost of available machines, timely unavailability of CA machines on hiring service and diverse cropping systems across the states.

Keeping in view the enormous economic and environmental benefits, globally the CA area is increasing and total CA area is about 180.44 m ha of which about 14% is in Asia (Kassam et al. 2018). For the success of CA adoption, the suitable machinery is a pre-requisite and under Indian conditions, two CA machines namely Turbo Happy Seeder (THS) and Rotary Disc Drill (RDD) have been successfully used for direct seeding of crops under surface residue conditions (Sharma et al. 2007; Sidhu et al. 2015; Chhokar et al. 2017). These machines work with improved efficiency, when crops are harvested using straw management system (SMS) fitted combine harvester or surface residue is chopped with rotary shredder prior to seeding operation. These CA machines have been discussed in details under the following heads:

14.6.1 Turbo Happy Seeder (THS)-CA Machinery

It is a CA machine, which allows direct seeding of crops in anchored as well as in loose residue. The front rotary unit of the machine is equipped with a PTO powered drum, on which flails are mounted in zig-zag way. The back of machine has seeding unit with inverted-T type furrow openers similar to zero-till drill. The flails mounted on rotary drum clears the residue in front of the tynes, which is followed by placing of seeds and fertilizer using seeding attachment of machine. The crop residues are accumulated between the crop rows (Sidhu et al. 2007). This machine is capable of seeding the crops under loose residue with a load up to 10 t ha^{-1}. The latest version of THS fitted with inverted gamma shape serrated flails provides the advantages of higher field capacity (11.1%) and lesser fuel consumption (28.3%) over previous version of THS (with inverted gamma shape plain flails) (Sidhu et al. 2015). Further improvement in THS such as using inclined plate planting mechanism and row markers can help in optimizing the seed rate and crop stand while lowering the chances of overlapping. The direct seeding of wheat with THS reduces the operational cost (50−60%), canopy temperature, evaporation losses and irrigation water demand over conventional practice (Sidhu et al. 2007, 2015). However, it works efficiently under dry crop residue condition, which limits its application in the late evening or early morning due to dew making the crop residue comparatively wet. Sidhu et al. (2015) recommended double disc furrow openers for effective and uniform seeding at greater forward speed.

14.6.2 Rotary Disc Drill (RDD)-CA Machinery

This is another resource conservation machine, which uses SoilRazor discs in PTO powered rotary cutting unit at front and seeding attachment with double disc furrow openers at back of the machine (Sharma et al. 2018, 2020). These discs are held in their position with proper spacing with the help of spools like in harrow. The discs of the machine are fitted straight without any disc angle for minimum soil disturbance and lesser power requirement. The saw tooth action of discs allows effective cutting of crop residue. A narrow slit of soil is opened by front discs, which is followed by aligned double disc furrow openers for placing of seeds and fertilizers. This machine can be used for direct seeding of crops in anchored as well as loose residue and provide similar or higher crop yield with lesser energy and cultivation cost compared to CT practice. Moreover, it can be used for seeding the crops in residue buried field (crop residue buried into soil without cutting like by MB plough), where problem of residue dragging is observed with non-rolling type furrow openers. In addition to rice residue, this machine can be used for direct seeding of wheat in sugarcane ratoons (Chhokar et al. 2017), which covers huge area in western Uttar Pradesh, India and where sugarcane trash burning is very common problem. The saw tooth curvature provides self-sharpening characteristics to discs and makes them effective in cutting of dry as well as wet hard residue. The adoption of such machine can bring more area of rice-wheat and sugarcane-wheat cropping systems under CA, thus diminishing residue burning and environmental degradation problems. The adoption of various resource conservation tillage technologies (RCTTs) will help in decreasing the cost of production and improving the soil health along with significant saving of labor and energy expenditure.

14.7 Crop Diversification/Intensification

The intense cultivation of rice-wheat cropping system in IGP caused adverse effects on soil physico-chemical properties, system productivity and groundwater table and increased weed infestation (Humphreys et al. 2010; Bhatta et al. 2016). Various workers reported that long-term intensive cultivation of rice affects the soil health (decreases soil aggregates, create hard pan), which hampers the soil quality as well as productivity (Kukal and Aggarwal 2003; Bhatta et al. 2016). Diversification of rice-wheat system by introducing the short duration legume crops for grains or green manuring in between rice and wheat can help in restoring the soil health by enhancing the physico-chemical properties and organic matter content of soil properties. Alternate cropping sequences like rice-potato-wheat, rice-pea-wheat, rice-wheat-greengram/green manure crops, maize-wheat-greengram, cotton-wheat and sugarcane-wheat, etc. are some of the options for the farmers depending upon the available resources and marketability of these produces. The intensification of cropping system (rice-vegetable pea-wheat; rice-potato-wheat) can provide better net returns to farmers over mono-cropping pattern of rice-wheat. The inclusion of short duration crops also provides better land use efficiency to attain the sustainable yields. The inclusion of greengram in wheat and barley based systems can improve the system productivity and net returns. Needless to say that timely completion of field operations plays main role in enhancing the cropping intensity. Amidst critical window period between crop harvesting and next crop seeding and labour scarcity problems, the use of direct seeding machines like THS and RDD can play the prominent role in intensification of rice-wheat cropping system. After wheat harvest, summer moong or fodder maize can be directly seeded using these machines, which provides improved agro-ecosystem and additional income to the farmers. Intercropping, relay cropping, cultivation of dual purpose crops and brown manuring can play the prominent role in enhancing the cropping intensity, system productivity and profitability, which are discussed under the following heads:

14.7.1 Intercropping

In future, to provide the food security to rising population, cropping intensity has to be increased through multiple cropping. This will increase the profit per unit area and per unit time (Seran and Brintha 2010). Intercropping of mustard in wheat and barley in 6: 1 ratio is found to be more profitable (Srivastava et al. 2007; Tripathi et al. 2005).

The cultivation of crops on raised beds can help in diversification of rice-wheat system. Raised bed system also provides an option of growing intercrops like sugarcane in furrows and wheat, gram, lentil, peas, mustard and various vegetable crops on beds. Manually operated seed drill can be used for inter-row sowing of oilseed crops like rapeseed and mustard in wheat and barley or moong in sugarcane crop especially for farmers belonging to marginal and small land holdings. It provides a field capacity of 0.3–0.4 ha day^{-1}. Additionally, individual seed and fertilizer box for each furrow opener also allows the sowing of various crops in one go.

14.7.2 Relay Cropping

Relay cropping is seeding of a crop in already established crop before harvesting. In cotton-wheat and cotton-barley systems, sowing of wheat and barley crops is often delayed due to delayed picking of cotton causing yield loss in these crops. Relay seeding of wheat and barley in cotton using relay or high ground clearance planters offers an excellent opportunity for timely sowing of crop and to improve the crop productivity and net profit to the farmers. Relay seeding of wheat increased the cotton yield by 11–14% due to one additional picking in extended growing period of about 30 days. Moreover, wheat yield was also increased by 25% with relay seeding due to timely planting of crop over conventional practice (Singh et al. 2020). Relay seeding of wheat in cotton using high clearance tractor provided 27–37% higher net returns to farmers as compared to conventionally sown wheat (Singh et al. 2016; Singh et al. 2020).

Intercropping of legumes provides nitrogen to the main crop and also adds humus in the soil due to decaying crop residues (Kheroar and Patra 2013). The legumes in rotation improves the soil fertility and the grain yield of subsequent cereal crop by release of N and other growth promoting factors through incorporation of legume residues (Shivran and Ahlawat 2000; Ghosh et al. 2007). Meta analysis of 45 studies in China, showed 14% higher yield with legume based rotation than non-legume rotation and this yield advantage was more under low dose application of N fertilizer (<120 kg/ha) (Zhao et al. 2020). Similarly, Sharma and Behera (2009) observed the beneficial effect of inclusion of grain legumes (greengram, cowpea and groundnut) in maize–wheat cropping system for improving productivity, profitability, N economy and soil fertility.

14.8 Dual Purpose Wheat and Barley

Sometimes, the farmers face the problem of shortage of green fodder for livestock during November, particularly in water scarce arid areas. In these areas, barley and wheat can be grown as dual purpose crops to avoid fodder scarcity. Dual purpose crop (wheat and barley) serve the purpose of nutrition rich green fodder and grain. For dual purpose wheat and barley, one cut of crop can be taken around 50–55 days after seeding (first node stage) and regenerated crop can be used for grain purpose (Sharma et al. 2019). About 25% extra seed and N fertilizer are required for dual purpose wheat and barley. However, it is crucial that appropriate agronomic practices are adopted to avoid higher yield loss. In dual purpose barley, the crop becomes less vulnerable to lodging due to significant reduction in height leading to comparable yield.

14.9 Irrigation

Water is the precious resource for crop production. Timely, uniform and need base application of water influences the efficiency of other inputs particularly fertilizers. More cropping area under irrigated conditions led to increased production over the years. However, slow recharge rate of water aquifers, continuous depletion of groundwater, increased water demand in non-agriculture sectors, uncertainty of rainfall and climate change have forced the researchers to explore the water efficient agricultural practices. It has been estimated that by 2025, 1800 million people will be living with absolute water scarcity (500–1000 m^3/year/capita), and two-thirds of the world's population could be living under water stressed conditions (<500 m^3/year/capita) (FAO 2021a). Moreover, India's per capita water availability, which was 5177 m^3 $year^{-1}$ will sharply reduce to 1306 m^3 $year^{-1}$ by 2031 and further down to 1174 m^3 $year^{-1}$ by 2051 (EnviStats India 2018). The semi-arid regions of Asia and Africa would be the worst affected areas in future. It has been anticipated that every 1 °C increase of temperature would require at least 10% higher irrigation water in arid and semi-arid regions of Asia (Hargreaves et al. 1993). After the green revolution in India, there is overexploitation of groundwater particularly in the rice-wheat system. The ground water resource has been declining at an alarming rate particularly in IGP and is a challenge for the future crop production sustainability (Rodell et al. 2009; Humphreys et al. 2010). Therefore requires urgent effective strategies for efficient water use and increased water productivity of crops.

Presently, surface irrigation is widely used irrigation method globally, which has low field application efficiency of about 40–60%. Further, the irrigation efficiency in India is approximately 40% (Jain et al. 2019), Under surface irrigation method, excess irrigation is applied to crop, which is associated with poor aeration caused by waterlogging, crop lodging, soil salinization and leaching of nutrients beyond the root zone.

Under surface irrigation method, the adoption of LLL and bed planting system saves substantial amount of irrigation water leading to improved water productivity. In bed planting, saving of significant amount of irrigation water is due to lesser irrigated covered area and further this saving can be increased by irrigating the alternate furrows. However, further efforts are needed to improve the WUE of crops by reducing the application and evaporation losses through irrigation scheduling and moisture conservation techniques. Water productivity of wheat ranges from 0.6 to 2.3 kg m^{-3} in India (Meena et al. 2018; Upadhyaya 2018) when irrigation scheduling is optimum under different growing conditions. Precision management of irrigation water can ensure proper soil moisture to support higher yield as well as high WUE in wheat and barley. The pressurized irrigation methods viz., drip and sprinkler irrigation method can address these challenges by supplying need based water to crop. Surface drip and subsurface drip irrigation (SSDI) systems provide higher water application efficiency of 70–90% due to sharp decline in runoff and deep percolation losses (Singh et al. 2020). The SSDI also provides reduced evaporation, reduced weed and diseases infestation, and increased water and fertilizer use efficiency along with better crop yield.

Sidhu et al. (2019) and Singh et al. (2020) reported that irrigation WP increased by about 150% and 100% in maize and wheat, respectively, under SSDI system over conventional method. In addition, a 25% saving of fertilizer N was achieved under fertigation in both maize and wheat without any yield penalty. Sandhu et al. (2019) reported that maize and wheat under surface drip irrigation with residue retention system showed significant grain yield increase of 13.7% and 23.1% compared to furrow irrigation with no residue, respectively. Surface drip irrigation with residue retention saved 88 mm and 168 mm of water and increased WP by 66% and 259% in wheat and maize on permanent beds compared to the conventional furrow irrigation system with residue removal, respectively. Subsurface drip irrigation also reduces the labour requirement for management of laterals and provides higher life of laterals. Under the scenario of unavailability of micro-irrigation systems, LLL and bed planting methods can be adopted under conventional practice, which provide the substantial water saving leading to improved water productivity of crops. In sandy or saline soils, adopting sunken bed practice, where crop plants are sown in the centre of furrow or side of beds and irrigation is applied in the furrows, a significant amount of irrigation water can be saved. This will also reduce the impact of salinity (salt accumulates on the top of beds) and water stress (moisture is available for longer period in furrow) on the crop plants.

Barley is a drought tolerant winter season crop and thus requires lesser irrigations compared to wheat. It requires irrigation at three critical stages viz. active tillering, flag leaf and milking stages. Under limited water resources, i.e. one irrigation only, then it should be applied at active tillering stage. If water is available for two irrigations then crop should be irrigated at active tillering and flowering stages. Since, barley is grown in light sandy soils for which sprinkler and drip irrigation methods are more appropriate. Sprinkler irrigation method is also suitable for undulating topography. When covering the large area in shorter time, rain gun sprinkler can also be used, which operates at high pressure and discharge. In general, hulless barley with 10–15 days longer duration than hulled varieties require one additional irrigation at grain filling stage for proper grain filling and to overcome the heat stress/hot winds damage. This holds true for malt barley also as this crop should not suffer from moisture stress at any stage of growing period.

The changes in cultivation practice can also enhance WUE of crops in irrigated as well as in semi-arid regions. In rainfed areas, farmers depend on rainfall to grow wheat and barley. However, erratic rainfall pattern adversely affects the production. Soils of these regions have low water holding capacity. Under such situations, proper soil and water conservation measures are the foundation for sustainable crop production. Therefore, the soil should be covered as much as possible with crop residue, which will also increase the infiltration rate. The better soil moisture content and infiltration rate under crop residue mulching can substantially increase the crop yields of rainfed regions. The adoption of CA can fulfill these objectives of irrigated as well as rainfed regions along with other multi-dimensional benefits. For instance, higher SOM in CA helps in better soil moisture retention in the root zone for a longer period leading to higher WUE. Moreover, with adoption of CA, pre-sowing irrigation can be avoided by utilizing the residual moisture of soil and seeding the crop immediately after harvesting of crop. This is feasible under rice-wheat system, where farmers go for direct seeding of wheat using ZT or THS after combine harvesting of rice fields. Avoiding pre-sowing irrigation and reduced irrigation water at first irrigation, CA (ZT + R) can provide 15–20% water saving in wheat. If this practice is followed over entire rice-wheat area, there will be a huge water saving (0.8 m litre ha^{-1}, if irrigation depth is 8 cm) (Singh et al. 2020).

In addition to method of irrigation, its proper scheduling also plays significant role in improving the yield and water productivity of crops. Irrigation scheduling at critical physiological stages and deficit irrigation application at the certain crop stages help in improving the crop productivity and water use efficiency (Capra et al. 2008; Lobell and Ortiz-Monasterio 2006) particularly where water is a limiting factor. Panda (2003) recommended irrigating wheat at 45% depletion of available soil moisture (ASM). In wheat, Crown Root Initiation (CRI) and earheading stages are the most critical to moisture stress. While in barley tillering stage is sensitive to moisture stress. Irrigation scheduling using tensiometers at 60–70 kPa was found effective in improving the yield and water productivity (Meena et al. 2018). Huang et al. (2005) suggested that proper combination of straw mulching and irrigation can result in higher crop yields in the semiarid areas. Recently, the micro irrigation practices even in close spaced crops such as wheat have shown the potential applications. The drip irrigation has the potential to double the increase the irrigation efficiency due to reduction in evaporation, surface runoff and deep percolation losses. Field studies carried out at Ladhowal, Punjab has showed that drip irrigation as well as fertigation in wheat based CA systems saved about 60% irrigation water and increased N use efficiency by 25% (rice, maize and wheat) compared to flood irrigation in CT system (Singh et al. 2020).

14.10 Nutrient Management

Availability of nutrients to the crops is one of the key factors for realizing the potential yield. However, globally the majority of the soils are deficient in different essential nutrients depending on the intensity and nature of the cropping system. Wheat and barley based intensified cropping systems are showing multi-nutrients deficiencies (N, P, K, S, Zn, Mn, Cu, Mg, B) due to imbalanced and improper fertilization in addition to reduced or absence of organic manures. The responses of wheat and barley to various micro- and secondary nutrients vary across locations.

The external application of nutrients is a must to sustain the intensive agriculture system. The use of feritilizer alone contributes about half of cereal production. For better nutrient management, it is essential to follow the 4R Nutrient Stewardship (apply at proper time, at proper place, at proper rate and from proper source) to match the crop's demand for nutrient, leading to minimum nutrient losses and maximum crop response (Roberts 2007; Sharma et al. 2020). Largely, the yield responses of wheat and barley to nitrogen or phosphorus application are wide spread and responses against potassium and other secondary and micro nutrients is limited. The high crop response to N is a forcing factor for over dosing of N fertilizers in wheat by the farmers (Singh et al. 2010). However, balanced fertilization is crucial to increase crop productivity and maintain the system sustainability in long-term.

Generally the farmers broadcast the fertilizer (N&P) at the time of crop sowing and compared to drilling its efficiency is low. The drilling or placement of fertilizer is important particularly for the nutrients less mobile in the soil such as phosphorus in deficient fertility and moisture conditions. It has been reported (Katyal et al. 1987; Gill et al. 2019) that application of nitrogen through urea just before irrigation gave higher productivity of wheat and better use efficiency as compared to urea application after irrigation. Also, urea should be applied uniformly for better use efficiency as there is negligible lateral movement along with water and it only moves downwards (Sharma et al. 2020). Nitrogen is a macro nutrient and crop respond to its application globally due to large scale N deficiency in soils. The N should be applied in 2-3 splits in wheat and barley for optimum yield. In rainfed the full doses of fertilizer should be applied at the time of sowing.

Farmers generally apply over dose application of inorganic fertilizer, which leads to adverse effects on soil and environment in addition to higher cultivation cost. The major problem with use of chemical fertilizers is their low use efficiency. The poor N use efficiency is mainly due to poor synchrony between N crop needs and N supply and by synchronization, N use efficiency can be improved. Also, the fertiliser recommendations are blanket based on the different growing conditions. Mostly the farmers apply N much higher than the blanket recommendations. Therefore, it is essential to adopt the integrated nutrient management practices rather than relying solely on in-organic fertilizers and need based fertilizer application technologies for improving the nutrient use efficiency.

Integrated Nutrient Management (INM) is an approach, where plant nutrient needs are met through use of mineral fertilizers; organic manures/fertilizers (e.g. green manures, recyclable wastes, pressmud, crop residues, FYM, etc.) and bio-fertilizers. Various studies showed that application of 12–15 t FYM/ha along with recommended doses of fertilizers result in higher wheat productivity and sustainable soil fertility (Sharma et al. 2013). This increase in crop productivity may be due to many components present in the organic manures and their effects on soil physico-chemical and biological properties. The higher fertility (150% recommended fertilizer along with FYM) has shown the significant yield improvement if lodfing is checked with growth regulators such as like ethephon and chloremequat chloride. Lodging is the main problem under high fertility conditions in barley and wheat crops.

Green manure (GM) crops are important source of N and organic matter. Important GM crops are *Sesbania aculeate/bispinosa*, *Crotalaria juncea* and *Tephrosia purpurea*. These crops can fix about 100–200 kg N/ha and can help in 50–75% chemical N fertilizers saving. The availability of several other plant nutrients is also increased due to favourable effects on soil chemical, physical and biological properties (Abdallahi and N'Dayegamiye 2000). It has also reported that incorporation of *sesbania* green manure (Meelu et al. 1994) along with wheat or rice straw improved the organic matter content and physical properties of soil. Leguminous green manures with narrow C:N ratio can be advantageously utilized for lowering down the C:N ratio of cereal residues. Seed treatment with Azotobacter, Azospirillum and PSB are also advantageous in wheat and barley. In addition, the new technology to be explored in future is nano fertilizers. Nano fertilizers contain plant nutrients mounted over nano (1–100 nanometers size) particles and the increased surface area offers better interaction with target sites (Janmohammadi et al. 2016). The advantages of nano-fertilizers will be that they are required in small quantities (60-100 times less) and can improve the nutrient use efficiency (2–3 times) than standard chemical fertilizers (Mikkelsen 2018).

In addition to fertilizer type and its application time, spatial and temporal variations are also responsible for inefficient N usage (Adhikari et al. 1999; Dobermann et al. 2003). Site-Specific Nutrient Management (SSNM) is a modern approach, which provides need based nutrients (as and when required) to crop leading to better nutrient management, improved nutrient use efficiency and higher crop yield. To apply the need based N to the crop, precision nitrogen management can be done using Leaf Colour Chart (LCC), SPAD and Green Seeker, techniques for improved nutrient use efficiency as discussed below.

14.10.1 Leaf Colour Chart for N Management

Leaf colour chart (LCC) technique developed by International Rice Research Institute, Philippines is a good indicator of nitrogen status of the plant. It measures the colour intensity of leaf, which is related to leaf nitrogen status. Nitrogen use can be optimized by matching its supply to crop's demand based on change in colour and chlorophyll content of leaf. The monitoring of leaf colour using LCC helps in determining the right amount and right time of N application. It is an ideal tool to optimize N use at reasonable high yield levels, irrespective of source of N applied – organic, biological or chemical fertilizer. In LCC approach, leaf colour is regularly monitored and N is applied when score falls below to threshold limit (leaves are lighter in colour).The use of LCC for nitrogen application is simple, easy and cheap under all situations. However, readings of LCC are affected by several factors such as variety, plant or tiller density, differences in solar radiation of two seasons, status of nutrients other than N in soil and plant, and biotic and abiotic stresses in the crop. The user needs to be careful in determining LCC score under such situations. It has been observed that about 10–15% nitrogen can be saved with LCC technique over conventional practice (Singh et al. 2020).

14.10.2 SPAD Values

SPAD chlorophyll meter indirectly measures the chlorophyll content of leaf based on SPAD score, which reflects the nitrogen status of plants. The SPAD meter value is determined based on the ratio of transmittance of red (650 nm) and infrared (940 nm) lights through the leaf (Hoel and Solhaug 1998; Uddling et al. 2007). It gives useful information on nitrogen status in plants and allows application of additional N depending upon necessity. Moreover, SPAD score at heading stage can effectively predict the grain yield (Bavec and Bavec 2001). Different SPAD values are used for different crops and varieties. For rice cultivars grown in IGP region of India, the threshold SPAD value of 37 or 37.5 has been found to be appropriate for optimum rice yields, whereas for rice cultivars grown in South India, the threshold SPAD value of 35 is suitable (Singh et al. 2020).

14.10.3 GreenSeeker Technology

GreenSeeker is an active type crop sensor and can be used for monitoring of the crop's health. The sensor works based on the crop reflectance i.e. magnitude of red and infrared beams reflected back from the plants. Unlike qualitative evaluation in leaf colour chart technique, GreenSeeker provides a quantitative index. The measured value is displayed in terms of normalised difference vegetation index (NDVI), an indicator of ground cover and the health of that cover. The monitoring of crops using remote sensing based instrument "GreenSeeker" helps in determining the need based application of nitrogen. By using a nitrogen rich strip, it can be determined that whether rest of the field requires additional nitrogen or not (Bijay-Singh et al. 2011). In this approach, a moderate fertilizer N (45 + 45 kg N/ha) is applied at planting and crown root initiation (21 DAS) and rest is guided using GreenSeeker at second and third irrigation leading to N saving without any yield penalty. The application of GreenSeeker technology in rice-wheat cropping system showed that more than 20% and 15% nitrogen can be saved in rice and wheat crop, respectively, without any yield reduction in both crops (Sharma et al. 2013). Bijay-Singh and Ali (2020) reported that GreenSeeker allows variable rate application of nitrogen and mapping, which can be used throughout the growing season. Greenseeker based N management resulted into similar (in rice) to higher yield (in wheat) with reduced N requirement, thereby increasing the nitrogen use efficiency (Bijay-Singh et al. 2011; Sharma et al. 2009). This technology has also applications in field of weed and diseases control (Sharma et al. 2020)

14.11 Weed Management

Weed infestation is also a major constraint in optimizing the resource use efficiency. The efficient weed management is needed for better resource use as well as for realizing the potential yield of crops. Wheat and barley are infested by both grasses and broad-leaved weeds. As wheat is mostly grown in irrigated conditions and is dominated by grass weeds, whereas, barley is mostly infested by broad-leaved weeds. The losses caused by weeds vary depending on the weed flora and their intensity as well as soil and environmental conditions. The average losses caused by weeds in wheat and barley range from 15% to 30% (Gill and Brar 1975; Chhokar et al. 2012). Barley is more competitive against weeds than wheat (Blackshaw et al. 2002) as barley has early vigorous growth and by active tillering stage, it completely covers the soil resulting in smothering of weeds. Plant height in wheat and barley is directly related with weed competitiveness and yield loss. Semi-dwarf and hulless cultivars of barley were found lesser competitive than tall and hulled cultivars (O'Donovan et al. 2017; Mahajan et al. 2020). In close spaced cereal crop, chemical weed control is preferred over mechanical and manual weed control options due to cost and time effectiveness. Also, the narrow spacing of wheat and barley as well as the scarce and costly manpower make manual and mechanical options as less feasible. Moreover, morphological similarity of some of weeds to crop cause escape during mechanical weeding, while these are effectively controlled by herbicides. However, the herbicide application should be at proper dose and time using appropriate method of application for better herbicide efficacy. Use of herbicides in combinations and mixtures is preferred due to control of complex weed flora as well as reduce the problems emerging from single herbicide usage such as weed flora shift and herbicide resistance evolution (Wrubel and Gressel 1994; Chhokar et al. 2012). However, sole dependence on herbicide is not desirable and non-chemical means of weed management should also be integrated with herbicides.

The adoption of mono cropping has led to some specialized weed problem in wheat and barley. Implementing effective crop rotation provides an opportunity to reduce the infestation of crop associated weeds. Rotating sunflower, berseem or sugarcane with wheat is effective to reduce the infestation of some of the problematic weeds such as *Phalaris minor* in wheat under rice-wheat rotation (Chhokar et al. 2012).

Stale/false seedbed technique is another effective strategy to reduce weed abundance by targeting the soil weed seed bank depletion. In false seed bed technique, weeds are encouraged to germinate by applying tillage and light irrigation followed by killing the emerged weeds with non-inverting tillage under CT system or non-selective herbicides under ZT system. Kanatas et al. 2021 reported trhat the dry weight of *Phalaris minor* and *Lolium rigidum* were 75–85% and 31–55% lower when false seedbed was applied compared to where direct sowing was performed. The combination of false seed bed with herbicide was better compared to herbicide application alone. Tillage practices also influence the distribution of weed seeds in soil and thereby affecting the seed bank and weed flora dynamics (Chhokar et al. 2007). Weed flora and growth is also affected by various growth resources. Increased usage of nitrogenous fertilizers replaced the leguminous weeds with grass weeds.

Pinoxaden at 30–45 g/ha is the best option to control grass weeds in barley (Chhokar et al. 2008). The efficacy of most of the post-emergence herbicide can be improved when applied along with adjuvants. Many researchers reported increase in herbicide efficacy and spectrum of weed control with usage of surfactant (Malik et al. 1988, Green and Green 1993; Chhokar et al. 2011). Certain fertilizer (urea ammonium nitrate and ammonium sulfate) also helps in improving the efficacy of herbicides. It has also been reported that ammonium sulfate overcomes the decreased herbicide activity due to antagonism caused by the presence of metal cations (Ca, Na, K and Mg) in spray solution (Nalewaja and Matysiak 1993).

For the control of grass and broadleaf weeds, combination of herbicides as either tank mix or ready mix or sequential are needed. In case of compatibility problem, these should be applied sequentially. Herbicide mixture in addition to diverse weed flora control will also help in managing and delaying the herbicide resistance problem (Wrubel and Gressel 1994). The evolution of herbicide resistance and weed shift are more frequent with continuous usage of solo herbicide. So, alternate herbicides and herbicide mixtures with different mechanism of action should be used.

Crop straw management also influences the weed control. Retention of crop residue on the soil surface is beneficial as it helps in weed suppression through mulching effect (Chhokar et al. 2009). Therefore, CA is also beneficial in weed management. However, timely effective control of initial flush of weeds is must in CA to obtain a comparable yield, as under this practice, weed control by tillage or interculture operation is left out.

As single weed management practice is not effective against dynamic weed flora over a longer period of time. Therefore, the integrated weed management approach should be followed to effectively combat the weed problem in a sustainable manner. Long term sustainable weed management should include the integration of chemical options (herbicide rotation, herbicide mixture) with non-chemical agronomic practices such as crop rotation, like stale seed bed, zero tillage, sowing time adjustments, residue retention, competitive cultivars, closer spacing and higher seed rate. The target should be to provide the competitive edge to the crop over weeds and depletion of the weed seed bank.

14.12 Harvesting and Threshing

Manual harvesting of wheat, barley and other crops is very laborious, time consuming and drudgery operation. It requires about 120–200 man-hours for harvesting one hectare area of wheat crop, giving an output of 0.2–0.4 ha day^{-1}. Labour scarcity problem is usually faced during the harvesting season. Any delay in harvesting of crop due to labour scarcity and longer time taken in manual harvesting may cause significant yield losses associated with shattering and weather uncertainty. Under such circumferences, farmers give prior importance to timely harvesting and threshing of crops with minimal losses. Vertical conveyer reaper (VCR) is a resource conservation option for harvesting of crops especially for farmers belonging to small and medium land holdings, who don't have their own combine harvesters or don't get timely hiring service of combine harvesters. It is an engine operated, walk behind type harvester suitable for harvesting of rice, wheat, barley, jowar, ragi, bajra, soyabean, etc. There are negligible shattering losses due to vertical conveying of the crop. It provides a field capacity of 0.1–0.2 ha h^{-1}. As compared to manual method, harvesting of crops with VCR results in lesser operational time (85%), reduced drudgery, low labour requirement (81%) and reduced harvesting cost (30–40%) (Singh et al. 2008; Murumkar et al. 2014; Debnath and Chauhan 2020). The losses in harvest operation are also reduced with VCR over manual harvesting of crops (Patel et al. 2018; Debnath and Chauhan 2020). Other similar harvesting machine, self-propelled reaper cum binder allows harvesting and binding of crops into bundles simultaneously. After cutting of crops such as wheat, paddy, oats, barley, etc. these are conveyed vertically to the binding mechanism, where crop is tied with polypropylene rope and released to the ground in the form of bundles. A higher cost of polypropylene wire remains a major disadvantage of this machine. The cutter bar mounted at front of tractor has also been used for harvesting of wheat and barley crops. It provides field capacity of 0.3–0.4 hah^{-1}. However, this practice results into higher shattering losses over harvesting of crops with VCR due to high vibration of tractor engine.

Threshing is considered a laborious and drudgery operation. Multi-crop power thresher seems to be good option, where harvesting of crops is done either manually or using VCR. It can be operated by stationary diesel engine, power tiller, electric motor or tractor PTO depending upon the power availability. Power thresher for multi crops are usually fitted with spike-tooth cylinder, which provides the opportunity to thresh multi-crops with a single machine, thereby saving the capital cost. Farmers belonging to marginal, small and medium land holdings having their own or accessibility to hiring service of this machine can utilize it for wheat and barley threshing. It is advisable to go for combine harvesting, where field size is comparatively large and famers have their own or timely hiring service of combine harvester as total losses in combine operation is lesser than individual operation of harvesting and threshing.

Farmers engaged in rice-wheat or other rice based cropping system with their marginal and small land holdings usually go for manual threshing of rice crop, which a laborious and slow process, giving a low output capacity. For farmers of hilly regions and other rice growing states like West Bengal, Odisha and Bihar, pedal or power operated wire loop paddy thresher has been marked as major intervention in threshing operation (Agrawal 2008). The farmers can thresh about 40–50 kg of grains per hour with pedal operated wire loop paddy threshers along with enhanced threshing efficiency (>96%), depending on crop variety, grain to biomass ratio, moisture condition and operational parameters (Agrawal 2008; Singh et al. 2008). If manual operation of powering the wire loop thresher is replaced with power source such as electric motor, internal combustion (IC) engine and photovoltaic cell, the output capacity of machine can be raised to 150–200 kg h^{-1}. However, solar powered wire loop thresher delivers the benefit of eco-friendly operation over IC engine powered paddy thresher (Sahu and Raheman 2020).

14.13 Conclusion

The conventional intensive agricultural practices have met the food grain demand, but simultaneously have degraded the natural resources. Some of the problems of conventional system are soil organic matter decline, soil erosion problems, soil structural degradation, multiple nutrient deficiencies, water table decline and increased GHGs leading to global warming problems. In conventional agriculture, intensive tillage practices, cereal-cereal mono-cropping, large scale residue burning and unbalanced application of fertilizers have gradually decreased soil organic carbon. The reduced input responses and increased secondary problems are responsible for the higher production costs and yield stagnation. Under such scenario, challenge of increasing food grain production to meet the future demand of growing human population from the decreasing resources particularly the land will be enormous. The adoption of good agronomic practices consisting of appropriate climate resilient cultivars, sowing time and methods, conservation tillage options, integrated nutrient, water and weed management can be helpful in increasing the productivity of wheat and barley along with conservation of resources. Adjustment in sowing time helps in counteracting the adverse effect of terminal heat stress, which is major cause of yield reduction in wheat and barley. By adopting no-till sowing along with residue retention, multi benefits such as moisture conservation, reduced tillage cost, temperature moderation, reduced weed growth and better soil health can be derived, which leads to higher crop productivity. The use of LLL and micro irrigation (sprinkler/drip) would be helpful in improving the water productivity and crop yield especially under water scarce areas. Integrated nutrient management can play the prominent role in tackling the emerging problem of soil health degradation and yield stagnation. Whereas, integrated weed management will resolve the problem of weed flora shift and emergence of herbicide resistant weeds. The integration of all these agronomic practices would provide positive impact on productivity and profitability of wheat and barley crops along with conservation of natural resources.

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Efficient Irrigation Water Management in Rice-Wheat Cropping System

15

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15.1 Introduction

Ever-rising demand of water in agriculture, industrial and other sectors would put enormous pressure before rising population for accessibility of fresh water. The accessibility to quality water is declining day by day. It has been estimated that India's per capita water availability will reduce sharply to 1306 cubic meter by 2031 and further down to 1174cubic meter by 2051 (EnviStat 2018). In Fig. 15.1, yellow line indicates that whenever per capita renewable freshwater water availability falls below to 1700 cubic meter per year then that particular region or country begin to experience water stress. Further, if freshwater availability decreases below to 1000 cubic meter per capita per year, water scarcity begins to affect human health and economic development of the region (Indicated by red line in Fig. 15.1). Agriculture is also going through intensified load due to pressure of burgeoning population on limited water resources. In such scenario, agricultural activities would be at risk especially in the regions having low rainfall (Sharafi et al. 2011). A major portion of available water is used for irrigation purpose in agriculture sector, which has 70% share in total water removal and 60–80% share in total consumptive water uses. The long-term predictive estimations of fresh water resources suggest a significant paucity in water availability, especially less rainfall receiving regions of the world, which calls for urgent innovative solutions and strategies for management of agricultural water.

Food security can be realized possibly through irrigated agriculture as irrigation doubles the crop yield in comparison to rain-fed farming by sustaining adequate soil moisture supply throughout the growing period (Lobell et al. 2009). The irrigated area needs to be augmented by at least 20% in order to aim for a 40% increase in

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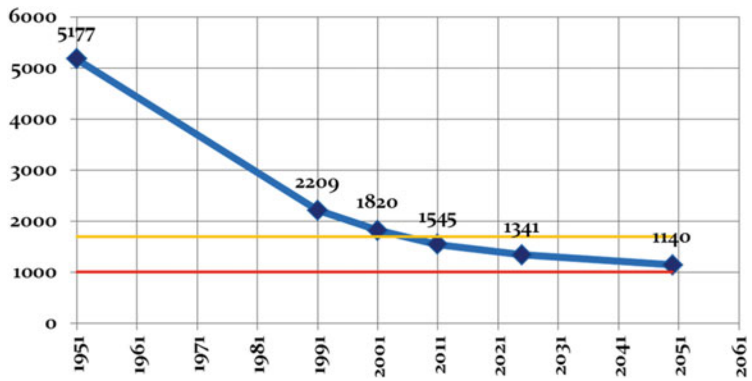

Fig. 15.1 Per capita water consumption of India

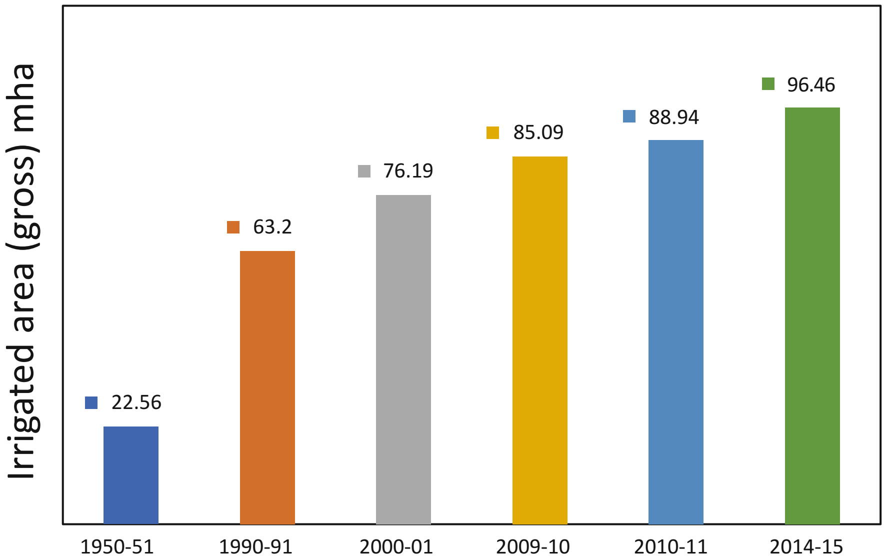

Fig. 15.2 Irrigated area developed since 1950–51 in India (Source: Land-use statistics 2014–15)

grain yield by 2025 (Lascano and Sojka 2007). India has made an impressive progress in bringing the area under irrigation since 1950 (Fig. 15.2). Rainfall, which primarily contributes in freshwater availability, is also likely to be negatively affected under climate change scenario. Study of 40 years' rainfall data of North West India by Narjary et al. (2014) showed decline trend of rainfall and its poor distribution over time and space. The demand for increasing the irrigated area under agriculture is estimated to hike the irrigation water requirement to the tune of 50% in developing and 16% in developed countries of the world by 2080 (Fischer et al. 2007). The estimated water consumption pattern of India is depicted in Fig. 15.3. It is

Fig. 15.3 Estimated water consumption pattern of India (Source: World Bank 2006, India's water future to 2025–2050)

clear from this figure that water consumption in other sectors continues to rise, which will reduce water availability for agriculture sector. Therefore, it is necessary to optimally use available water resources for better water productivity (WP) in which agricultural water management is a key factor.

Rice–wheat followed by cotton–wheat, maize–wheat, and millet–wheat are important cropping systems covering about 14.59 mha area in India. Percent irrigated area under major cereal crops is presented in Fig. 15.4. It can be observed that major area of wheat, barley and rice crops falls under irrigated conditions. Excessive water demand and lesser water productivity in rice–wheat cropping sequence under traditional irrigation practice caused to deplete the surface and groundwater in India, which in turn forced the researchers around the globe to find out new crop management strategies to address such challenges. Needless to say that productivity and input use efficiency of rice-wheat and other cropping patterns needs to be enhanced considerably to meet the food grains demand of bludgeoning population in future. However, limited water availability and inefficient use of water are the major hurdles in up scaling the crop yield. Among cereal crops, rice is a major water consumer crop, which 2500 L of water to produce 1 kg of rice (Bouman 2009). In rice cultivation under irrigated condition, major water losses occur through evapotranspiration (ET) and soil percolation processes (Kukal and Aggarwal 2002; Bouman 2009).

Rice and wheat (RW) are the main cereal crops globally and is the backbone of India's food security, which accounts more than 70% share on total food grain production. However, intensive cultivation of rice-wheat especially in Indo-Gangetic plains (IGP) region has led to deterioration of water and other natural resources. Future of irrigated RW system in India is threatened by continuous declining groundwater table (Hira 2009). Therefore, systematic efforts are required through interventions of inexpensive and environmentally-sound water conserving techniques to address the issue of declining water resources. The water productivity

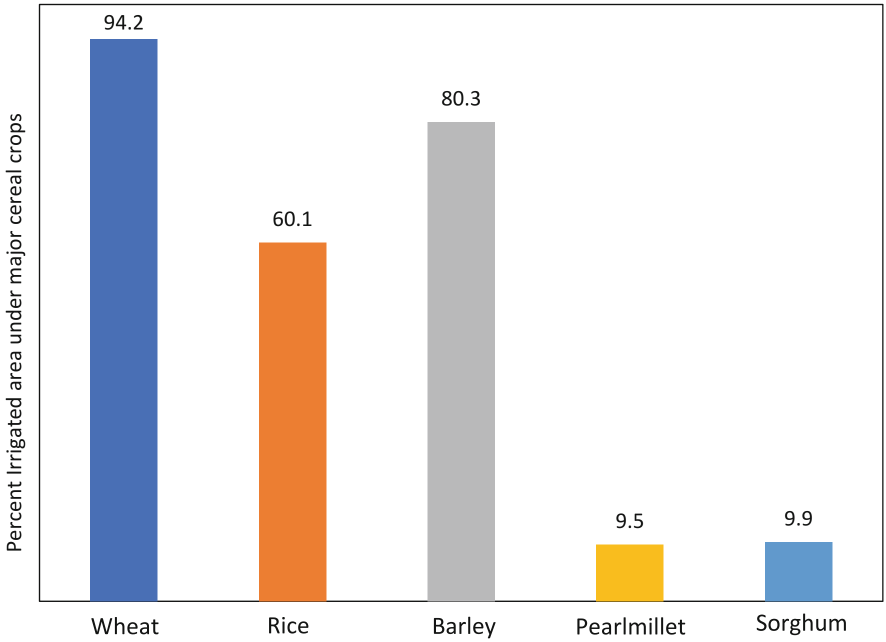

Fig. 15.4 Percent irrigated area under major cereal crops in India (Source: land-use statistics 2014–15)

(WP) can be enhanced by efficient use of water i.e. either bringing out higher crop with given amount of water or bringing out similar crop with lesser amount of water. In conserving the water and increasing the WP of crops, water management through appropriate interventions such as irrigation scheduling coupled with improved crop management techniques would play the crucial role.

15.2 Extent of Groundwater Usage for Irrigation and WP

In last few decades, depth of groundwater table rapidly increased under intensive rice-wheat cultivation in IGP region (Hira 2009; Rodell et al. 2009), which would not be sustainable in long-term. India is biggest consumer of ground water accounting for 25% share in global water consumption, making it larger consumer than China and USA combined together (Margat and der Gun 2013; Mukherjee et al. 2015). Possibly the ground water levels in India are declining at the fastest rate in the world (Aeschbach-Hertig and Gleeson 2012). In last three decades, groundwater table declined by 8–16 m and 1–8 m in north-western India and rest region of the country (Sekhri 2013). In fact, declining rate of groundwater table has reached to about 1.0 m yr.$^{-1}$ in wheat growing regions of Punjab and Haryana states during the last decade, which was about 0.2 m yr.$^{-1}$ between 1973 and 2001 (Yadvinder et al. 2014; Singh and Kasana, 2017). Such drastic change in groundwater table is one of the main reasons causing to make India a home for 25% of world' population living under water scarce conditions (Mekonnen and Hoekstra 2016).

Presently, WP of wheat in India is estimated as 0.8–1.06 kgm^{-3} (Zwart et al. 2010; Meena et al. 2015), whichis close to global mean WP for wheat (0.90 kgm^{-3}). However, WP of wheat in India is much below to that of China, which is estimated to be 1.3 kgm^{-3}for irrigated wheat uniformly distributed across the country (Brauman et al. 2013). It has been found that WP of rice varies in the range of 0.24–0.57 kgm^{-3} across the rice cultivating states of India (Sharma et al. 2018). It was relatively high ($>$ 0.50 kg m^{-3}) in the states of Punjab, West Bengal, and Assam whereas, it had lower value (0.24–0.28 kgm^{-3}) in the states of Bihar, Madhya Pradesh and Karnataka (Sharma et al. 2018).

15.3 Irrigation Water Management Approaches for Maximizing WP

Water productivity denotes the amount of output resulted from quantity of input used over unit area. In agriculture, it may be expressed as crop yield per unit amount of water consumed (kg yield per m^{3}water) according to scale of reference used, which may include or exclude water losses. The term water productivity terms has been used by various stakeholders with different scales and aim (Table 15.1). Primarily, the term 'irrigation/water-use efficiency' was applied to find out working performance of irrigation system. However, in agronomical aspects, the term 'water use efficiency (WUE)' refers to production of organic matter with unit amount of water consumed by the plant in this process. Water Productivity (kg/m^3) of important cereals and pulses crops in India has been presented in Table 15.2. Needless to say that the term, 'water use efficiency' lacks the classical concept of 'efficiency', where same units are applied to input and output. Considering such non-uniformities, International Water Management Institute (IWMI) has suggested to change the terminology water use efficiency' to 'water productivity'.

Table 15.1 Meaning of water productivity terms used by various stakeholders

Stakeholder	Meaning	Scale	Aim
Agronomist	Yield-to-evapotranspiration ratio	Field	Adequate food
Plant physiologist	Dry matter-to-transpiration ratio	Plant	Utilize light and water resources
Farmer	Yield-to-irrigation ratio	Field	Higher income
Irrigation engineer	Yield-to-canal water supply ratio	Irrigation scheme	Proper water allocation
Policy maker	Net profit-to-available water ratio	River basin	Higher net profits

Table 15.2 Water Productivity (kg/m^3) of important cereals and pulses crops in India

Rice	Wheat	Finger millet	Maize	Sorghum	Pearl millet	Barley	Pigeonpea	Gram	Greengram
0.12	0.5	0.2	0.14	0.4	0.27	0.4	0.11	0.54	0.12

Source: Kapuria and Saha (2020)

15.4 Irrigation Scheduling

Irrigation scheduling is the process, where decision on when and what magnitude of irrigation is to be put in a crop is made. It aims to supply appropriate quantity of water to the plants at specific developmental stages based on their demand in order to realize more crop yield and water productivity. Irrigation scheduling is basically practiced in different ways viz., 1. Measuring the soil water potential directly to find out the soil water demand; 2. Using the 'soil water balance calculations', where the amount of water lost from soil (in the form of runoff + drainage + evapotranspiration) is deducted from quantity of water supplied to the soil (irrigation + precipitation); 3. Critical crop growth stage approach (farmer friendly approach); 4. Soil moisture depletion approach; 5. Atmospheric evaporativity approach; 6. Irrigation water (IW) at different cumulative pan evaporation (CPE) levels and 7. Agronomic approaches such as laser leveling, seed priming, mulching, deficit irrigation methods, bed planting, micro irrigation etc.

15.5 Evapotranspiration (ET) and Soil Water Balance Approach

Irrigation timing is planned by taking the total water depletion and readily available water (RAW) into account (Huffman et al. 2013).

$$RAW = MAD * (\theta fc- \theta pwp) * Dr. \quad (15.1)$$

where, RAW is expressed in L, Dr. is referred as root zone depth, MAD is referred as management allowed depletion, θfc denotes volumetric Θ at field capacity (L^3*L^{-3}) and θpwp indicates volumetric Θ at permanent wilting point (L^3*L^{-3}). The magnitude of θfc and θpwp vary with soil types and these can be taken from previous study by Huffman et al. (2013).

It is well known that crop water requirement (WR) is calculated at all growth stages of a crop. The irrigation scheduling using evapotranspiration (ET) and soil water balance (WB) approach is an effective and water conserving technique to meet the water demand of a crop. In this approach, precise estimation of ETc play crucial role, which can be calculated using different calculations and decision support tools such as CROPWAT 8.0 by taking the soil, climate and crop data into consideration. The methods for direct measurement of ETc such as lysimeter, field water balance, etc. are costlier, labour intensive and time consuming. So, usually, it is done by measuring the reference evapotranspiration (ETo) and multiplying it with crop coefficient (*Kc*). The calculation of *ETo* can be worked out using meteorological data in FAO Penman-Monteith equation. The magnitude of *Kc* is generally selected by the way of single or dual crop coefficient, when both crops are assigned different crop transpiration (*Kcb*) and evaporation (*Ke*) coefficients values (Allen et al. 1998). Needless to say that estimation accuracy of ET-based method strongly influenced by (1) accuracy in estimation of ETo, (2) creating an improved crop coefficient (Kc) curve during the growth stages either through single/dual crop coefficient or location-specific calibration method (3) effectiveness in assessment of soil properties for determining water holding level of soil, and (4) computing location-specific rainfall (Davis and Dukes 2010). The performance of ET-based irrigation scheduling approaches depends on various in-field management practices. In many cases, it has been observed that ET-based irrigation scheduling approach could not be successful due to decline in crop yield over conventional irrigation practice (Hunsaker et al. 2015) as a result of allowing lower soil water content during the crop growth stages. Devitt et al. (2008) observed that automatic irrigation scheduling according to ET data ensured water saving in 81% of ET-based controllers, which were site-specifically programmed with manufacturer's recommendations.

15.6 Soil Moisture-Based Approach

InΘ-based irrigation scheduling methods, irrigation is triggered based on monitored value of Θ (inferred from sensor measurements) and threshold value Θ. The monitored value of Θ is can be computed by time specific transmission sensors, reflection-based and neutron probes, granular matrix sensors, etc. (Thompson et al. 2007; Hedley and Yule 2009; Migliaccio et al. 2010). Other soil moisture measuring device namely tensiometer (as shown in Fig. 15.5) can be used for measuring the soil water tension or soil matric potential (ψm) to find out water accessible to plants, which is relevant to Θ-based irrigation scheduling. Θ-based irrigation scheduling can be adopted for applying the irrigation at an appropriate stage in order to maintain root zone Θ within the set range, thereby improving the crop growth, yield, water productivity and quality of output (Viani 2016).

Various approaches have been adopted for fixing the irrigation according to critical or threshold value of Θ, θth (Zotarelli et al. 2010; Haley and Dukes 2012). Θth depends on soil properties, crop type, species, yield and other agronomical management practices. It is decided based on various field experiments exploring the effect of water stress levels under different irrigation treatments on the crop response (Wang et al. 2017). Θth values are optimized according to site-specific conditions and crop species. The benefit in Θ-based irrigation scheduling is that it permits adjustable rate irrigation according to in-field variability of spatial and temporal Θ. Therefore, spatial variability in amount of irrigation required in various sections of the field could be an alternate approach to sensor array method (Vellidis et al. 2008, 2013). Hedley et al. (2013) worked out the possibility of using electromagnetic mapping method in preparing the map of soil moisture status and soil properties as well as available water content (AWC) and θfc to find out the Θth value for executing the irrigation (Hedley and Yule 2009). Electromagnetic mapping method provides better spatial resolution in Θ and soil properties, which enables it to prepare θth map with higher resolution and executes the adjustable rate irrigation scheduling more accurately over other methods employing conventional sensors for measuring the Θ values (Hedley and Yule, 2009). Needless to say that effectiveness on Θ-based irrigation scheduling is strongly dependent on the accuracy of Θ measurements and in absence of Θ accuracy, this method could be disadvantageous over conventional irrigation practice (Evett et al. 2011). In actual practice, Θ sensors are employed to

Fig. 15.5 Tensiometer installed in the field

monitor the trend of soil moisture, which is then integrated with other irrigation scheduling approaches. In this approach, irrigation is scheduled at particular soil depth according to soil matric potential (SMP), which is directly related to energy required by the crop to extract water from soil profile. The most common methods of determining SMP are manually read tensiometers, and granular matrix sensors. Tensiometer measure real time SMP ranging from 0 to about −80 kPa, which covers the range needed by most cereal crops.

15.7 Plant Water Status Approach

The working of plant-based irrigation scheduling methods utilizes the correlation between crop water stress and soil water deficit along with taking physiological and phenological status of crop into consideration. Plant sensitivity to water stress depends on its species, tissues, and crop phenological levels. In past, plant stress based various approaches have been suggested for irrigation scheduling. Among plant stress based irrigation scheduling, Jones (2004) observed two major groups:1. plant water level based–direct quantifying the water level of leaf/xylem/stem and indirect quantifying other parameters such as leaf thickness, variability in diameter of stem and fruit, and turgor pressure (Padilla-Díaz et al. 2016); and 2. plant physiology based–quantification of sap flow, xylem cavitation, stomatal conductance, and thermal sensing. It is noteworthy to mention that in plant stress based irrigation scheduling, direct and indirect measurements of parameters related to water status and plant physiology should be accurate enough for proper evaluation of water status in plant/crop (Jones 2004). Irrigation based on phenological stages of crop is another way for irrigation scheduling. In wheat, water stress to plants at any critical growth stage i.e. at crown root initiation (CRI), tillering, jointing, flowering, milking and at dough stage may cause significant yield loss depending upon stress level.

15.8 Simulation Model Output Approach

Irrigation scheduling is done with the help of various approaches and simulation of process-based model. In regression-based models, irrigation scheduling is performed through optimized algorithms derived from soil water balance equation. In past, various models based on crop's growth process along with consideration of soil-crop-atmosphere effects had been tested to improve precision in irrigation scheduling. The models such assoil and water assessment tool (SWAT), CROPWAT, AquaCrop, and Root zone water quality model (RZWQM2) have been adopted for simulating crop response to water level and environmental parameters in irrigation scheduling. RZWQM2 model provides accurately simulation of crop responses under varying environmental, soil and management conditions (Ahuja et al., 2000; Ma et al. 2012). CROPWAT, developed by FAO, is one of the effective decision support tools for determining the irrigation water demand using climatic variables and crop data (Smith 1992; Savva and Frenken 2002). CROPWAT utilizes ET-WB technique, which also provides the prediction of yield reduction in response to water stress levels (Doorenbos and Kassam 1979). It needs data of climatic variables, crop and soil. In CROPWAT, irrigation can be activated by Θth value, at regular interval pre-decided based on allowable depletion in water or ET level. Under such practice, water is applied until Θ value reach back to θfc. The calculations details for triggering action and irrigation scheduling through CROPWAT tool are detailed in previous study by Doorenbos and Kassam (1979) and Allen et al. (1998). Smith et al. (2002) evaluated the performance of CROPWAT tool in irrigation scheduling under restricted irrigation conditions. This tool has also been adopted to find out optimal irrigation scheduling (Feng et al. 2007; Augustin et al. 2015).

15.9 Agronomic Approaches for Efficient Irrigation Water Use

In the scenario of rising food demand and declining quality of natural resources, researchers and farmers need to adopt climate-resilience and resource conserving agricultural technologies and practices to improve crop productivity and net income in an economically sound manner. The large scale implementation of climate-resilience agricultural practices would be helpful for farmers to adapt variable weather patterns amidst deteriorating natural resources. For example, groundwater table is falling at an alarming rate in north-western Indian states due to intensive cultivation of rice-wheat cropping system, slow rate of groundwater recharging from erratic rainfall and overuse of electric pumps driven by subsidised electricity. As per estimation every 1° C increase in temperature would demand at least 10% additional irrigation water in low rainfall regions of Asia. A major portion of groundwater is consumed in irrigation activities and there is need to adopt concrete steps on implementation of water conserving technologies to reverse the water declining trend and to avoid water-scarce condition in future. Therefore, adoption of efficient agronomical technologies for improving the water productivity would be helpful in this mission.

15.9.1 Precision Field Leveling

Usually, agricultural fields are roughly levelled and some parts of field experience water stress while other parts undergo surplus water condition, which lead to loss in crop yield. Under uneven field condition, irrigation water and other inputs especially nutrients are used in an inefficient way. Precision land levelling optimally utilizes the available resources resulting in higher input use efficiency and cropping area as area covered under bunds and channels significantly reduces. Thus, adoption of laser land levelling technique would be helpful to produce more crop per drop of water.

Laser land leveler is a modern implement for land levelling which consists of scrapper, hydraulic system, transmitter, receiver and control box as main components. It precisely levels the land which improves uniformity of water application, while reducing the irrigation water (20–30%) and abiotic stress intensity, thereby improving crop yield (10–20%) and water productivity (Jat et al. 2006; Kaur et al. 2012). Jat et al. (2005) reported that precision leveling resulted into higher water productivity of rice (0.91 kg m^{-3}) and wheat (1.31 kg m^{-3}) as compared to water productivity of these crops as 0.55 and 0.82 kg m^{-3}, respectively, under conventional practice. The key benefits of using laser land leveler are given below:

Key benefits of laser land leveler (Jat et al. 2006, 2009, 2014; Latif et al. 2013, Aryal et al. 2015)

- Laser land leveling reduces irrigation application time by 10–12 h ha^{-1} in wheat and50–60 h ha^{-1} in rice crop per season.
- 5–26% improvement in rice and wheat yield
- Up to 750 kWh annual saving in electricity for one hectare area under rice-wheat system.
- 2–6% increase in cropping area
- 27–64% increase in NPK uptake efficiency
- Reduction in weed density and labour/chemical required for weed control.

Needless to say that laser land leveling technique has been marked as notable intervention for improving performance of crops under surface irrigation method. However, despite multiple benefits, adoption of laser land leveler on large scale has been low due to constraints such as high capital investments, high power requirement and less efficient operation in small sized farms (Jat et al. 2006).

15.9.2 Seed Priming Technology

In the scenario of reducing the input cost of crop cultivation, it is a pre-requisite that all seeds drilled into soil should be readily germinate and produce vigrous seedlings for better crop yield. In seed priming, controlled hydration of seeds is performed to achieve a sufficient level to enable the preparatory processes essential for germination, without allowing protrusion of the primary root. The performance of seeds under limited moisture conditions or germination of newly harvested or older seeds can be improved by means of seed priming, which may otherwise fail to meet the objective of proper germination and plants stand (Binang et al. 2012). Harris (1996) reported that germination and emergence rate can be enhanced by allowing the seeds to soak in water prior to seeding operation, which results in higher plants stand and more vigorous growth of seedlings. Priming was seen to promote to earlier tillering, maturity and higher grain yields. Seeds can be primed with little concentrated phosphate in order to promote the early root growth permitting the plants to use soil P effectively. Rajpar et al. (2006) reported that before performing seeding operation, priming the seeds with freshwater can enhance the yield of wheat crop. Effective germination and proper plant stand provides the competitive advantage to crop against weeds and raises tolerance to unfavourable moisture regimes, thereby enhancing the crop yield (Clark et al. 2001). Seed priming method provides multiple benefits such as increased germination and emergence rate, proper and uniform plants stand, higher tolerance to water stress situations, flowering at early stage and improved yield in some crops (Harris et al. 1999; Harris and Hollington 2001; Shabbir et al. 2014). Even under sub-optimal moisture conditions, seed priming enhanced the growth and yield-contributing characters of wheat (Meena et al. 2015).

Direct-seeded rice is an alternate rice cultivation practice, which allows timely planting of rice with 20–30% lesser labour and water costs over conventional practice of rice transplantation (Lee et al. 2002). In this cultivation practice, it is necessary to have higher germination rate of seeds and uniform plants stand as directly sown seeds may experience lesser temperature, water stress, surplus water and other unfavourable conditions. Seed priming can address these challenges under this practice. Moreover, it also provides higher antioxidant enzyme, improved antioxidant level, increased oxidative defensive enzymes activity and vigour to seeds (Kaklewski et al. 2008; Roqueiro et al. 2012).

It has been suggested that priming can be achieved by seed treatment with micronutrients (Farooq et al. 2012), a better alternative in many cases, compared to other methods. According to these authors, seed priming with zinc can increase seedling emergence, establishment and subsequent growth as well as productivity.

Another important micronutrient is boron and researchers reported that conditioning rice seeds with boric acid resulted in greater establishment of rice seedlings (Rehman et al. 2012).

15.9.2.1 Crop Establishment Method

Zero tillage (ZT) is the simple and in expensive technique, which allows timely seeding of wheat i.e. advancing the seeding of wheat by about 10–15 days after harvesting of paddy crop over conventional practice. It provides beneficial effects in both wheat and rice crops, thereby increases the net income of farmers. Wheat seeding by ZT system combined with seed priming technique saves time, fuel, labour and most importantly one irrigation (pre-sowing irrigation) by using residual moisture of field just after harvesting of rice (Meena et al. 2013). It has been found that ZT reduces irrigation water by about 10 cm in wheat crop as it cuts down evaporation rate in addition to utilizing the residual soil moisture from previous rice crop (Malik and Balyan 2002). Many researchers observed upto30% savings in irrigation water with ZT technique in wheat crop (Hobbs and Gupta 2003; Humphreys et al. 2005). Erenstein and Laxmi (2008) found 5–7% higher wheat yield in ZT practice after harvesting of rice due to timely seeding of wheat, over conventional practice. ZT practice in wheat under rice-wheat cropping pattern in IGP region can save a huge amount of irrigation water (about one million L) and diesel fuel consumption about 98 L per hectare area in addition to reduction in associated harmful air pollutants (Pathak et al. 2009).

Rice is a water guzzling crop as it is grown under submerged conditions. Rice grown under irrigated conditions like in wheat is known as direct seeded rice (DSR), which can reduce the irrigation demand and improve the water productivity. DSR is broadly adopted in rainfed uplands, lowland and in flood prone areas. DSR, help farmers to earn more carbon credits than transplanted rice by mitigating methane emission, saves water and has higher economic returns. DSR is a resource conserving technology, which helps in reducing the water consumption due to elimination of raising seedlings in nursery, puddling and transplanting processes and associated water demand. The elimination of these processes also saves energy (electricity and diesel) and time in addition to reduction in harmful air pollutants associated with fossil fuel burning. Kumar and Ladha (2011) reported DSR yield in the range of 4.5–6.5 t ha^{-1}, which was 20–30% lesser than yield of lowland varieties cultivated with flooding practice. However, rice cultivation with this practice required 60% lesser water, thereby achieving 1.6–1.9 times higher water productivity and about two-fold higher net returns to water use over transplanted rice (Kumar and Ladha 2011). In other studies, water saving of 25–30% in DSR compared to transplanted rice was reported in NW India under silty loam soil (Kamboj et al. 2012; Gathala et al. 2014).

15.9.3 Mulching/Residue Retention

It has been estimated that about 23 million tons of rice residue is burned every year (National Academy of Agricultural Sciences). In view of critical window period of 20–25 days between rice harvest and wheat sowing, timely unavailability of suitable residue handling machines on hiring service, higher cost and power requirement of direct seeding machines, poor feed quality of rice residue and time and labour cost involved in manual handling of rice residue, farmers adopt injudicious practice of residue burning to ensure timely wheat sowing in an economical and rapid way. The burning of rice or other crop residue converts various important elements retained in the plants to harmful gases and particulate matter (Jain et al. 2014), which degrades the air quality in addition to loss to important nutrients (Moefc 2019; Shyamsundar et al. 2019). A few researchers reported rice residue burning as one of the major factors responsible for seasonal increase in air pollution of north-western plains of India (Jain et al. 2014; Sharma and Dikshit 2016; Cusworth et al. 2018; Chakrabarti et al. 2019; Shyamsundar et al. 2019). It has been found that various important nutrients such as C, N, P, K and S retained in crop residues are lost by 20–100% upon burning and convert to various toxic and particulate matter (Jain et al. 2014). Residue burning is also associated with loss of organic carbon and microbial population present in soil causing to decline the crop yield. In such scenario, farmers have to apply additional fertilizer to maintain the similar yield, thereby raising the input cost in crop production (PAU 2014).

Rice residue burning can be minimized through adoption of various in-field residue management methods such as retaining it on the soil surface and allowing direct seeding of wheat under zero till conditions using suitable machinery. Retaining crop residue on soil surface provides multiple benefits such as reduced evaporation rate, lesser irrigation water demand, erosion control and better controlling of weeds. About one-third part of water required to meet crop ET demand is lost by soil evaporation process, which provides only marginal contribution in crop yield. It has been found that direct seeding of wheat under zero-till or reduced tillage condition while maintaining the residue of previously harvested crop as mulch on the soil surface is effective in conserving the soil water especially in dry periods (Verhulst et al. 2011; Sidhu et al. 2015). Many researchers observed higher water productivity of crop with rice residue retention (RRR) over conventional practice due to soil moisture conservation phenomenon arising from reduced evaporation losses (Meena et al. 2020; Jat 2015; Sharma et al. 2011). With adoption of retaining crop residue on soil surface, farmers can reduce one irrigation demand, which would be accounted for more than 15% saving of irrigation water.

15.9.4 Deficit Irrigation Approach

It is always desirable to precisely meet the need base water demand of crop during all stages for its better growth, development and yield. Such needs can be met by irrigation scheduling technique, which eliminates the possibility of surplus irrigation

(Meena et al. 2018). Applying water excessive to demand as in conventional irrigation practices causes waterlogging and leach down of nutrients beyond root zone. The WUE of crops can be increased by suppling just sufficient water to crop through proper irrigation scheduling (Qiu et al. 2008). Full surface irrigation is commonly adopted practice by the farmers in water abundant as well as in water deficient regions. With such practice, all requirements for full evapo-transpiration of crops are fulfilled in order to produce the maximum yield but now-a-days, under groundwater depleting scenario, full irrigations are seen as luxury use of water, which can be cut down with marginal or no consequences on net profit. The level of reduction in irrigation water depends on crop type and it should be limited to cause no or marginal yield loss for better water productivity and net profitability (Ahmadi et al. 2010). Therefore, implementing modern irrigation techniques on large scale can play prominent role in enhancing the WUE of crops. Fulfilling the need base water demand at critical growth stages of a crop is advantageous over conventional practice, where huge volume of water is supplied to crop field. A few researchers reported water saving benefits underregulated deficit irrigation technique (Oweis and Hachum 2006; Peake et al. 2008, 2016; Meena et al. 2019a) are available. In fact, deficit irrigation (DI) technique allows the plants to take up water stored in soil profiles through deeper rooting phenomenon in the crop. The adoption of deficit irrigation (DI) technique in wheat cultivation can save up to 25–33% irrigation water (i.e. up to two out of six irrigations required at critical growth stages) without any yield penalty (Prihar et al. 1976; Meena et al. 2019b).

15.9.5 Bed Planting

Bed planting is an alternate to flat cultivation system in which crop seeding is performed on the top surface of raised beds. It is usually done with the help of bed planter, which forms the raised beds of specific dimensions and simultaneous planting of crops and fertilization is done with seeding attachment fixed at back of the machine. In case of wheat, generally three rows with 17 cm spacing are planted on the top surface of bed (35 cm width). Irrigation is applied in the furrow (30–35 cm width) between two consecutive beds. The furrow space allow allows cultivation of additional crops such as sugarcane, mentha and other vegetables. In bed planting, ridge acts as crop management while furrow area is considered as input management region. The consecutive arrangement of ridge and furrow in this cultivation system provides multiple benefits such as lower runoff losses, improved percolation and increased surface area for capturing rainfall and sunlight in addition to facilitation of draining out excess water under high rainfall events (Sayre et al. 1997; Tripathi et al. 2017). This cultivation system allows the cultivation of vegetables and other crops in furrow area in addition to wheat as primary crop on ridge area without any need of additional resources.

The planting of crops on raised beds may be beneficial especially in the regions, which are experiencing decline in groundwater table, water logging problems in monsoon season and decline in factor productivity. In this cultivation system, water is slowly absorbed from furrows to ridges and then it is moved upwards through capillary, evaporation and transpiration processes for plants grown on the top surface of beds. The design parameters (top width, bottom width and side slope) of beds are determined based on soil type, cropping system, spacing between tractor tyres, rainfall are of prime importance. For major soil types (sandy loam and loamy soils), 67 cm width (top width of raised bed as 37 cm and furrow width as 30 cm) is generally considered in rice-wheat cropping system. Bed planting allows up to 25–50% saving in irrigation water under rice-wheat cropping pattern with a yield similar to conventional practice.

15.9.6 Micro Irrigation System

Modern irrigation techniques play a key role in enhancing water use efficiency of irrigation system. Drip irrigation system, a kind of micro irrigation, is one of the effective methods for supplying water and nutrients directly to plant roots, which saves significant amount of water. Surface irrigation is widely used method of irrigation commanding more than 80% irrigated area worldwide, which has practical application efficiency of 40–50%. In contrast to surface irrigation, drip irrigation efficiency ranges between 70–90% as conveyance, surface runoff, deep percolation and evaporation losses are reduced, thereby improving the water productivity and profitability of crops (Postel 2000; Bhaskar et al. 2005). Micro-irrigation allows the plants to quickly use water and available nutrients leading to better growth and higher crop yield over surface irrigation. This irrigation system provides congenial environment leading to assimilate more metabolizable carbon and N in plants and root absorption surfaces for improved production efficiency (Hao et al. 2008; Meena et al. 2013). Patel et al. (2006) reported that upto 50% irrigation water can be saved through micro irrigation system while maintaining the soil moisture tension at low level during all growth stages of a crop. It provides just sufficient water to plants according to crop's evapotranspiration demand and ensures optimum soil moisture during all critical growth stages of crop leading to enhanced WUE (Kipkorir et al. 2002).

15.10 Real Time Feedback Based Irrigation Scheduling in Micro Irrigation Systems

Micro irrigation systems with open loop structure are manually controlled and are incapable to respond automatically based on climatic conditions. Due to manual operation of these systems, there may be some delay in water application to crops under irrigation scheduling based on some preset indicators (soil moisture, ET, etc.) and by that time plants could experience some stress which affects crop yield and water productivity. Coolong (2013) recommended optimized drip irrigation scheduling for maintaining a similar yield with lesser irrigation water and reduced weed growth. Therefore, these problems can be avoided in real time feedback based micro

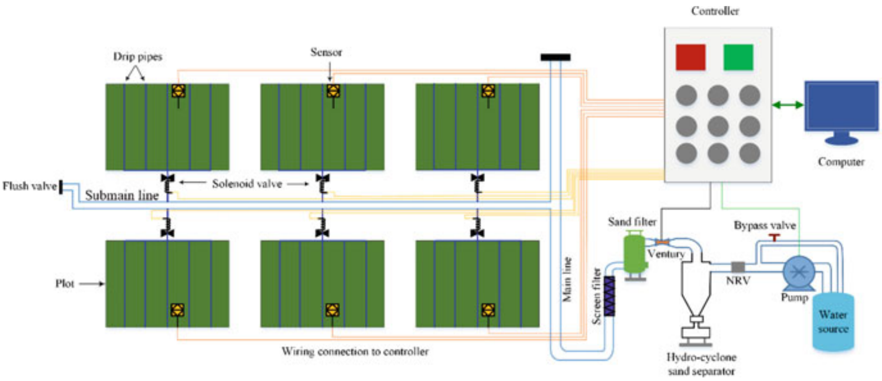

Fig. 15.6 Schematic representation of automatic drip irrigation system

irrigation systems which fulfills the dynamic demand of plant effectively. A schematic representation of automatic drip irrigation system is given in Fig. 15.6 In this system, field is divided into smaller plots. Various sensors (moisture, temperature, relative humidity, etc.) provide the feedback to controller which actuates pumping unit and respective valve by means of solenoid actuation. If field is not very large, a wireless system with emitters and receivers could be good choice over wiring system. Real time feedback-based irrigation scheduling in micro irrigation systems could be an effective approach for further improvement in crop water productivity.

15.11 Evidences from RW System on Irrigation Water Productivity in Western Indo-Gangetic Plains

At ICAR-IIWBR.

Study 1: In this study, effect on different irrigation treatments on performance of wheat was evaluated in terms of water use, yield and water use efficiency for three consecutive years. Wheat yield with 25% deficit irrigation (45 mm) was found at par to yield under full irrigation condition (60 mm of water) maintained at all five critical growth stages of crop. On further reducing the irrigation level to 50% (30 mm), a yield penalty of 10.9% was observed but it saved 50% irrigation water. Among all irrigation treatments, the maximum WUE of 2.23 kgm^{-3} was recorded for treatment having 25% deficit irrigation (45 mm) as compared to 1.88 $kgm^{-3}$for full irrigation condition in sandy loam soils. A huge amount of irrigation water (750 m^3ha^{-1}) was saved under 25% deficit irrigation (45 mm) without any yield penalty in wheat, which also provided other benefits of lesser electricity and labour cost. Therefore, application of 45 mm irrigation at all growth stages of wheat could be effective to improve the water use efficiency of crop along with other benefits such as reducing the irrigation water amount, pumping cost and associated harmful air pollutants, where diesel engines are used for irrigation purpose (Meena et al. 2019b). The adoption of such irrigation practices is the need of the hour especially in water and air quality depleting regions like IGP.

Study 2: In this study, influence of rice residue retention (RRR) on yield and yield attributes of wheat was investigated under restricted irrigation conditions. Retaining the rice residue on soil surface improved the wheat grain yield (5224 kg ha^{-1}), crop biomass (11.9 tha^{-1}), tillers per square meter (469), grains per meter square (13,917), relative water content (93.8) and WUE (2.45 $kg.m^{-3}$) significantly over treatment without rice residue. The profitability (Net return = $ 624.4) was also higher under RRR practice. Applying K through foliar sprayled to higher grain yield (5151 kg ha^{-1}), crop biomass (12 t ha^{-1}), RWC (94.1), SPAD (52.2), WUE (2.40 kg m^{-3}), net returns (625.2 $) and BC ratio (1.62) over treatment without foliar application. Retaining rice residue on soil surface and applying only one irrigation at CRI stage increased the grain yield and WUE by 15.66% and 17.39%, respectively, along with additional revenue of $ 151. The adoption of RRR practice on large scale can provide higher income to small and marginal farmers over existing practices in addition to reducing the negative impacts on environment (Meena et al. 2020).

Study 3: In this study, it was found that retaining the crop residue @2.5 tha^{-1} provided higher grain yield of 5.73 tha^{-1}along with net return of ₹ 42,645 ha^{-1}over treatment without any crop residue. The frequent application of irrigation in lesser amount using tensiometer based irrigation scheduling saved significant amount of water. The highest WUE was observed to be 1.95 kg m^{-3}under irrigation scheduling at 80 kPa followed by 1.45 and 1.11 kg $m^{-3}$for irrigation set at 60 kPa and critical growth stages, respectively. The highest yield was observed under irrigation scheduling at 80 kPasoil-water tension level. It was found that scheduling the irrigation at 60 kPa provided more yield along with efficient irrigation operation over water application at all critical growth stages (Meena et al. 2018).

In a different experiment, effect of seed priming was assessed on plant germination, growth, productivity and WUE of wheat crop subjected to various moisture regimes. Matriconditioning led to earlier germination of seeds than non-primed seeds, thereby providing better plants stand under ideal, sub-ideal soil moisture and air-dry soil conditions. It was found that matriconditioning improved the germination rate, plants stand and seedling growth (Meena et al. 2015, 2018).

Study 4: The minimum WUE of 1.32 kg $m^{-3}$was recorded under check basin method. A grain yield of 5545 and 5475 kg $ha^{-1}$was observed under drip+rainpot and drip treatments, respectively, in wheat crop. The WUE of wheat under these treatments was found as 1.57 and 1.55 kg m^{-3}, respectively. In rice, applying irrigation with drip led to higher grain yield over sprinkler irrigation system. From this study, it can be concluded that the highest WUE in wheat was achieved under drip+rainpot practice while in case of rice, it was observed under drip irrigation system (Meena et al. 2015). In another study, different irrigation methods were evaluated for wheat crop in which, the highest water productivity of 1.61 kg $m^{-3}$was observed under drip irrigation followed by 1.60 kg m^{-3} for drip + rainpot method with an average productivity of 5539 kg ha^{-1}. A huge amount of irrigation water (about 600 m^3ha^{-1}) was saved in seed priming method, which reduced the cultivation cost by Rs. 382 ha^{-1}. Among all irrigation treatments, the maximum amount of water was saved under drip irrigation followed by sprinkler and drip + rainpot. It was concluded that drip irrigation system coupled with seed priming technology can enhance the crop yield while reducing irrigation water requirement and associated input cost through efficient utilisation of water (Meena et al. 2018).

Study 5: Plant breeding approaches for enhancing WP involve identification of novel germplasm processing genetic ability to produce higher yields at an optimum or lower level of water supply. Here we illustrate this approach with one of the experiments conducted at ICAR-IIWBR, Karnal which identified higher WUE wheat germplasm lines. This study involved screening of seventy-one genetically diverse wheat genotypes for higher WUE while restricting soil moisture level to 60% of ETc. After screening, WUE wise top 16 genotypes were selected for field experiment. Restricted soil moisture level was maintained by supplying precise quantity of water in the root zone through micro irrigation system. Pearson correlation identified GY ($r = 0.99$), AGBM ($r = 0.46$), HI ($r = 0.86$), TGW ($r = 0.52$) and SCMR ($r = 0.46$) at post-anthesis stage, which led to increased WUE. In multiple comparison Tukey's test, the highest WUE of 2.40 kg $m^{-3}$was found for DBW 243 followed by 2.17 kg m^{-3}, 2.19 kg m^{-3} and 2.14 kg $m^{-3}$for 47IBWSN 938, DBW 166 and DBW 222 genotype, respectively. The higher WUE was resulted from improved harvest index. Such identified genotypes with higher WUE could serve as a useful resource for researchers in developing water use efficient cultivars having higher yield. Moreover, other traits related to WUE could act as a selection criterion in breeding of wheat suitable for arid and semi-arid regions. Needless to say, that adoption of genotypes having higher WUE would reduce the irrigation water requirement in crop cultivation (Meena et al. 2019a).

Other Evidence: A field experiment evaluating the influences of conservation agriculture (CA) based management practices on yield, water productivity, profitability and soil quality was conducted in basmasti rice-wheat cropping system under farmer's participatory mode for 4 years. Six treatments included variations in cropping pattern, tillage method, crop establishment and residue management practices. It was found that system yield was 36% higher for rice-wheat-mungbean system under zero-till practice of CA-based management over conventional practice of rice-wheat cropping system (14.91 Mg ha^{-1}). Also, about 35% irrigation water was saved in CA-based rice-wheat and rice-wheat-mungbean system as compared to traditional practice ofrice-wheat cultivation (2168 mm ha^{-1}). In CA-based cultivation of rice-wheat-mungbean system, total water productivity (0.90 kgm^{-3}) was 67% higher as compared to traditional practice of rice-wheat cultivation.

15.12 Conclusion

In this chapter, we have described different approaches to minimize the irrigation water losses while adopting the improved and advanced irrigation methods for improving the water productivity. Integration of conservation agriculture approaches with drip irrigation methods may help in saving precious irrigation water and increasing water productivity under different cropping systems. Crop management approaches like zero tillage, seed priming, crop establishment, residue management and fertilizer management should be integrated with real time water availability using modern methods and sensors to get higher water productivity. In rainfed ecosystem, regulated deficit irrigation approaches are key to get higher water productivity and more profitability. Novel approaches like sub surface drip irrigation should be promoted to catch the attention of farmers and to achieve the more crop per drop.

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16 Fertilizer Consumption in Wheat Production Systems: Trends and Policies

K. V. Praveen and K. S. Aditya

16.1 Introduction

Wheat is an important source of food for the majority of the people in the world (Igrejas and Branlard 2020). According to an estimate, it provides 20 per cent of calories and proteins for about 4.5 billion humans living in 94 developing nations (Braun et al. 2010). Humans have cultivated wheat for more than 10,000 years, and by the nineteenth-century wheat has become one of the most cultivated crops in the world (Bonjean 2016). It is said that wheat cultivation has co-evolved with human civilization (Angus et al. 2011), and there are several records on the past of wheat cultivation and how it spread to different parts of the world (Weiss and Zohary 2011; Flandrin and Montanari 1996; Branlard and Chiron 2016). With the development of plant breeding and other fields of science, wheat production also increased rapidly allowing countries to meet the demands of the increasing population (Angus et al. 2011). The use of modern, input responsive varieties with high yield potential was promoted during the 1960s as a part of the green revolution, particularly in South Asian countries. The success of the green revolution was credited to the superiority if these varieties, increased input use and supportive policies.

The fertilizer intensive wheat cultivation, promoted during and post green revolution era has played an important role in increasing the yield levels but is also blamed for the damage it caused to the environment. The decrease in yield response of the wheat to fertilizer use is also a concern as reported from different parts of the world (Hawkesford 2014; Xu et al. 2020). However, the fertilizer use in most of the crops in most of the countries is increasing (Philips and Norton 2012). Considering the concerns of sustainability and environmental pollutions, the focus of farming needs to be shifted in favour of sustainable and responsible production systems to

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meet the food requirements of the increasing population (Reeves et al. 2001). For this to happen, understanding the status of fertilizer application is sine-quo-non. Tracking spatial and temporal trends in fertilizer use is essential to understand whether the production systems are directed towards the right path moving ahead. In this chapter, we examine the chemical fertilizer use in the case of wheat production. Along with the global scenario, our discussion focuses also on the Indian case simultaneously, India being a large wheat producer as well as a consumer. We first provide a brief overview of wheat production in the world and India, followed by the extent of fertilizer use and a brief discussion on the fertilizer policies.

16.2 The Status of World Wheat Production

Wheat is a crop that is grown in diverse geographies, ranging from sea level to over 3500 m asl, and from the equator to latitudes above 60 N in Canada, Europe, and Asia. CIMMYT has classified the total wheat production environment into different mega-environments (MEs) to prioritise wheat improvement (Rajaram et al. 1993). The MEs are formed based on the similarity in adaptation patterns, crop production factors, consumer preferences etc. and not necessarily based on geographical proximity (Hodson and White 2007). Originally the MEs were designated based on the simple criteria involving the level of rainfall and temperature (Braun et al. 1997). This exercise was later supplemented by adding climatic and edaphic factors utilizing GIS tools (White et al. 2001). For this, the long-term average of minimum temperature in the coolest quarter of the year is utilized to differentiate the winter-grown spring, winter/facultative, and summer-grown spring wheat (Fig. 16.1). The same strategy was followed to separate ME1 (favourable, irrigated) from ME5, where heat tolerance is required. The ME 1 to ME 6 represents the spring wheat MEs that occupy about 95 million hectares in the developing countries (China not included). The next category of facultative/winter wheat MEs (ME 7 to ME 9) covers 25 million hectares (Dubin and Rajaram 1996). Of all the MEs, the spring wheat environment, where about 40% of the developing world's wheat is produced is considered the most important one. The favourable, irrigated, ME1 environment occurs predominantly in India, Pakistan and the Middle East and Egypt (Hodson and White 2007), and the ME 6, ME7 and ME 10 are located in China. While the ME 1 to ME 4 and ME 6 falls mostly in the temperate regions, ME 7 to ME 9 appear in moderately cold, and ME 10 to ME 12 falls in severe cold regions (Pingali and Rajaram 1999).

The global production of wheat is 734 Mt. (Million tonnes) in 2018 produced in an area of 214 Mha (Million hectares) with an average yield of 3.4 tonnes per ha. From 1961 to 2018, the wheat production and yield has increased at a rate of 2 per cent, and the wheat area has increased by almost 0.1 per cent per year (FAOSTAT 2020). It is predicted that by 2050, the demand for wheat may increase by almost 60 per cent (Rosegrant and Agcaoili 2010), meeting which would be a challenge considering climate change and resource depletion. At present China, India, the USA, Russia and France are the top wheat producers in the world.

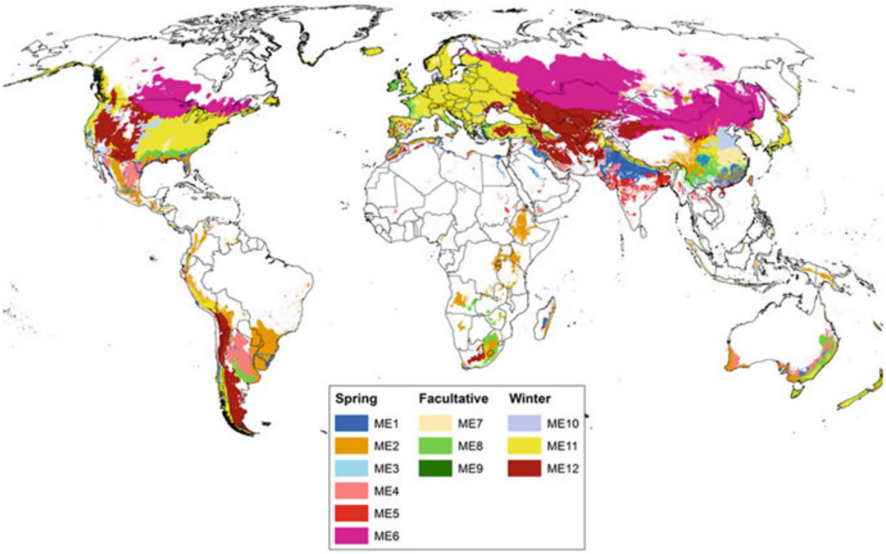

Fig. 16.1 Global map of wheat mega-environments (Source: Sonder 2016)

China and India contribute 17 and 13 per cent respectively to the global wheat production. The top five wheat producers together contribute more than 50 per cent to the total wheat production. In terms of area harvested, India stands top with a value of 29 million ha in 2018. Russia, China, the USA and Kazakhstan are the other countries in the top five list. While the share of India in total wheat area of the world is 14 per cent, that of Russia, China and the USA are 12, 11 and 7 per cent respectively. France appeared in the list of top five producers and harvested wheat just in an area of five million tonnes that is equal to a share of 2 per cent of the global area. It is very interesting to note that none of the countries that appeared in the list of top five producers and area harvested could seal a spot in terms of yield. The highest yield in 2018 was recorded by New Zealand with a value of 8.9 tonnes/ha. Netherlands (8.8 tonnes/ha), Ireland (8.7 tonnes/ha) and Belgium (8.4 tonnes/ha) followed it. The United Kingdom is the other country that appeared on the list with a yield of 7.7 tonnes/ha.

16.3 Wheat Production in India

The contribution of wheat towards the food security of India is unquestionable. The role of wheat in India's food and nutritional security can be understood from the fact that the crop is procured and distributed to a great extent by the government of India itself through the system of Minimum Support Prices and Public Distribution System (Aditya et al. 2017; Ramadas et al. 2019). India's wheat production has reached the all-time highest value of 109 Mt. in the year 2020–21 (second advance estimates).

Table 16.1 Wheat growing zones in India

Zones	States/regions covered	Area (million ha)
Northern Hill Zone (NHZ)	Hilly areas of J&K (except Jammu, Kathua and Samba districts), Himachal Pradesh (except Una & Paonta valley), Uttarakhand (excluding Tarai region) and Sikkim	0.8
North Western Plains Zone (NWPZ)	Punjab, Haryana, Western UP (except Jhansi Div), Rajasthan (excluding Kota & Udaipur div), Delhi, Tarai region of Uttarakhand, Una & Paonta valley of HP, Jammu, Samba & Kathua districts of J&K and Chandigarh	11.55
North Eastern Plains Zone (NEPZ)	Eastern UP (28 dist), Bihar, Jharkhand, West Bengal, Assam, Odisha and other NE states (except Sikkim)	10.5
Central Zone (CZ)	MP, Gujarat, Chattisgarh, Kota & Udaipur Div of Rajasthan & Jhansi Div of UP.	5.2
Peninsular Zone (PZ)	Maharashtra, Tamil Nadu (except Nilgiris & Palani Hills), Karnataka, Andhra Pradesh, Nilgiris & Palani Hills of Tamil Nadu	1.7

Source: GoI 2020; Ramadas et al. 2019

The estimates for the next years are still higher. The crop is cultivated in about 29 Mha area in the country and is divided into five zones. The north western plains zone and north eastern plains zones are the major areas where wheat is grown (Table 16.1). This region falls majorly in the Indo-Gangetic Plains, where intensive rice-wheat crop rotation with high levels of input use like fertilizers and irrigation is practised. Wheat yield in India, which was merely 850 kg/ha in 1960 increased drastically to reach 2200 kg/ha in 1990 and further to 3368 kg/ha in 2017. Between 1950 and 2018, while the area under wheat cultivation increased at a rate of 1.6 per cent per year, the production increased at 4.1 per cent and yield at 2.5 per cent. The area expansion under wheat took place during the decades of 1950s, 1960s and 1970s, and the yield enhancement mainly occurred during the 1960s, 1980s, and 2010s.

Wheat production in India has increased at an annual growth rate of nearly 4 per cent, since the introduction of high-yielding varieties and it elevated the importance of wheat crop in achieving food security (Singh et al. 2013). Among the states, Uttar Pradesh is the prime one in terms of wheat area and production (Table 16.2). The state contributes 32.54 per cent to the national area under wheat and 32.75 per cent to the production. Punjab, Madhya Pradesh, Haryana and Rajasthan are the other leading wheat producers. In terms of yield, Punjab tops the table with a value higher than 5000 kg/ha followed by Haryana (4925 kg/ha) and Rajasthan (3501 kg/ha). Many wheat varieties, suiting to different agro-climatic conditions, have been developed and released for cultivation by both public and private sectors which played a crucial role in enhancing wheat production in the country. The PBW, GW, HD and HI varieties are some of the varieties that occupied the wheat-producing area of the country in the post-2000 era. Many good varieties with varied yield potential, suitability and resistance to biotic and abiotic stress conditions has meant that the

Table 16.2 Major wheat producing states of India 2018–19

State	Area (million ha)	% to All India	Production (million tonnes)	% to All India	Yield (kg/ha)
Uttar Pradesh	9.54	32.54	32.74	31.60	3432.00
Madhya Pradesh	5.52	18.83	16.52	15.95	2993.00
Punjab	3.52	12.01	18.26	17.63	5188.00
Rajasthan	2.88	9.82	10.08	9.73	3501.00
Haryana	2.55	8.71	12.57	12.14	4925.00
Bihar	2.16	7.36	6.47	6.24	2998.00
Maharashtra	0.83	2.85	1.25	1.21	1497.10
Gujarat	0.80	2.72	2.41	2.32	3020.00
Uttarakhand	0.33	1.12	0.95	0.92	2910.00
Himachal Pradesh	0.32	1.09	0.56	0.55	1770.00
Others	0.87	2.97	1.78	1.71	2038.00
All India	29.31	100.00	103.59	100.00	3533.44

Source: GoI 2021

varietal diversity is maintained. Maintaining a varietal diversity at the aggregate level is important as it has implications for not just production but also with risks associated (Smale et al. 2003); If most of the cropped area is under only one variety, the production system is prone to more risks. Agricultural systems that lack genetic diversity have been proved to be vulnerable to biotic and abiotic stresses of various kinds and magnitude (Frankel and Bennett 1970; Smale 1997). It is therefore important to influence and modify the genetic diversity to benefit the agricultural performance of the crop along with making it more sustainable. Among the major wheat-producing states of India, in general, the spatial diversity in varieties has been found higher in the states of Uttar Pradesh and Madhya Pradesh and lower in Punjab and Haryana (Praveen et al. 2017a).

16.4 Consumption Trends in the World

Food production for the rapidly increasing world population required the adoption of newer technologies and increased use of agrochemicals; higher use of chemical fertilizers to avoid the nutrient depletion of agricultural land, and pesticide and herbicides to prevent crop loss. We examine the nutrient use in wheat crop, with a special focus on India. This is important since the pressure of food production may affect the soil nutrient balance hence necessitating a balanced application of nutrients for sustainability. The total consumption of fertilizers for agriculture use has increased continuously over the years. In the year 2018, about 186 million tonnes of fertilizer nutrients were consumed across the globe. The N consumption, which was 11 million tonnes in 1961 increased to 108 million tonnes by 2018, growing at an annual rate of more than 4 per cent. P and K use has also increased during the period, but at a much lower growth rate of 2.3 and 2.6 per cent respectively. The current usage of P and K are 40 and 38 million tonnes respectively. As previously mentioned, fertilizer use is not uniform across regions. While, Asia, Europe and North America consume the major chunk of fertilizers produced in the world, its consumption in regions like Africa is yet to reach the desired levels. Among the countries, China tops the list with the highest consumption of N, P and K fertilizers. India is also a key player in the global fertilizer market, and it depends on both production as well as imports to ensure adequate domestic fertilizer supplies. At present, India stands second in the world production and consumption of nitrogen fertilizers (FAI 2021). Besides, it stands third and second respectively in the production and consumption of phosphorous fertilizers. Potash fertilizers are not produced in India, but it is the fourth largest consumer of this nutrient. It is also the second-largest producer of urea and DAP in the world. Although imports have decreased in the recent periods, especially after the year 2010, still it is a very important component of the Indian fertilizer market, since it constitutes about 38 per cent of the total fertilizers consumed in the year 2018–19. About 26 per cent of nitrogen, 45 per cent of phosphorous and entire potash fertilizers are imported for use in Indian agriculture.

16.5 Fertilizer Consumption Trends in India

In India, the consumption of fertilizers has increased continuously over the years. It increased from 69 thousand tonnes in 1950 to 5.5 million tonnes in 1980, and then to 28 million tonnes in 2010. Consumption of fertilizers have not grown much after the year 2010, and it has decreased by about one million tonnes between 2010 and 2018. Nitrogen is the highest consumed primary nutrient (65% in 2018), followed by phosphorous (25%) and potash (10%). The nature and status of nutrient consumption among various Indian states are different, owing to the agro-climatic diversity, the difference in innate fertility and cropping patterns. Uttar Pradesh (16.70%) and Maharashtra (11.01%) uses the highest amount of fertilizers in terms of nutrient content, followed by Karnataka (7.16%), Madhya Pradesh (7.03%), Andhra Pradesh (6.80%), Punjab (6.72%) and Gujarat (6.58%). These seven states account for 57.09 per cent of the GCA of the country together receives 62 per cent of the total fertilizers consumed in the country. It is also worth mentioning that these states are dominated by fertilizer intensive crops like paddy, wheat, sugarcane and cotton. The states of Assam, Jharkhand, Chattisgarh, Odisha, Himachal Pradesh and Jammu & Kashmir, Uttarakhand, Kerala and Tamil Nadu together receive a share of less than 12 per cent in comparison to their 15 per cent share in GCA. The states in disadvantageous position however are the ones like Rajasthan and Madhya Pradesh since they receive a much lesser share of fertilizers in comparison to their share in GCA. In contrast to this, Uttar Pradesh, Andhra Pradesh, Punjab, Haryana and Telangana benefits through greater fertilizer share than share in GCA. Most other states receive fertilizers almost equal to their share in GCA (Praveen et al. 2017b).

16.6 Fertilizer Use for Wheat Production in the World

Compiling information on crop-wise fertilizer use is a daunting task as the data is scarce. International Fertilizer Association is one organization that keeps track of the crop-wise fertilizer use across major fertilizer consuming countries. The latest of their report provides data for the year 2014–15, which suggest maize to be the crop with the highest share in total fertilizer consumption. Maize consumed 29.4 million tonnes of fertilizers in 2014 that amounts to a share of 16.2 per cent (Table 16.3). Wheat stands second in the list of top fertilizer consuming crops with a share of 15.3 per cent. Between 2010 and 2014, the total fertilizer consumption by wheat has increased marginally from 27.1 million tonnes to 27.9 million tonnes. In terms of fertilizer nutrients, wheat is the largest consumer of N and P. While 18.2 per cent of the total N consumed in the world is for wheat production, its share in P is 14.6 per cent. However, the N consumption by wheat between 2010 and 2014 decreased slightly from 18.9 to 18.7 million tonnes. During the same period, the consumption of P and K by the crop experienced a small increase from 6.5 to 6.7 per cent, and 1.7 to 2.5 per cent respectively. Other than wheat and maize, the key crops consuming

Table 16.3 Crop wise fertilizer share

Crop	Share in total fertilizer use (%)	Share in N fertilizer use (%)	Share in P fertilizer use (%)	Share in K fertilizer use (%)
Wheat	15.3	18.2	14.6	7.4
Rice	13.7	15.2	12.5	11
Maize	16.2	17.8	13.9	14.2
Other cereals	4	4.7	3.6	2.7
Soybean	5.4	1.1	9.7	12.3
Oil palm	2.7	1.4	1.9	8
Other oilseeds	4.6	5.3	4.5	2.8
Fibre crops	3.7	4.1	3.8	2.4
Sugar crops	4.1	3.6	3.6	6.3
Roots/Tubers	2.3	2.1	2.5	2.5
Fruits	7.2	6.1	8.8	8.5
Vegetables	8.6	7.4	9.9	10.6
Grassland	4.3	4.7	4	3.8
Residual	7.8	8.3	6.7	7.6

Source: Heffer 2017

Table 16.4 Fertilizer consumption for wheat production in selected countries 2014

Country	Nutrient consumption for wheat production, quantity in kt				Share in fertilizer consumption for wheat in the world (per cent)				Share in total domestic consumption (per cent)			
	N	P	K	N + P + K	N	P	K	N + P + K	N	P	K	N + P + K
China	3396	2013	965	6374	18.2	30.0	39.1	22.9	13.5	13.2	11.8	13.1
India	3949	1275	261	5485	21.1	19.0	10.6	19.7	23.3	20.9	10.4	21.4
EU-28	3281	581	494	4356	17.5	8.7	20.0	15.6	29.2	22.6	16.9	26
USA	1561	563	170	2294	8.3	8.4	6.9	8.2	13.2	13.3	3.7	11.1
Pakistan	1359	449	12	1819	7.3	6.7	0.5	6.5	41	46	35	42.1
Canada	773	242	100	1115	4.1	3.6	4.1	4.0	30	25.5	25	28.4
Russia	609	215	74	899	3.3	3.2	3.0	3.2	41	35	21	36.6
Turkey	627	245	6	878	3.4	3.7	0.2	3.2	42	43	5	40.3
Australia	553	286	35	874	3.0	4.3	1.4	3.1	39.3	31.1	14.9	34.2
New Zealand	9	7	3	18	0.0	0.1	0.1	0.1	2	2	2	2
World	18,699	6699	2467	27,866	100	100	100	100	18.2	14.6	7.4	15.3

Source: Heffer 2017

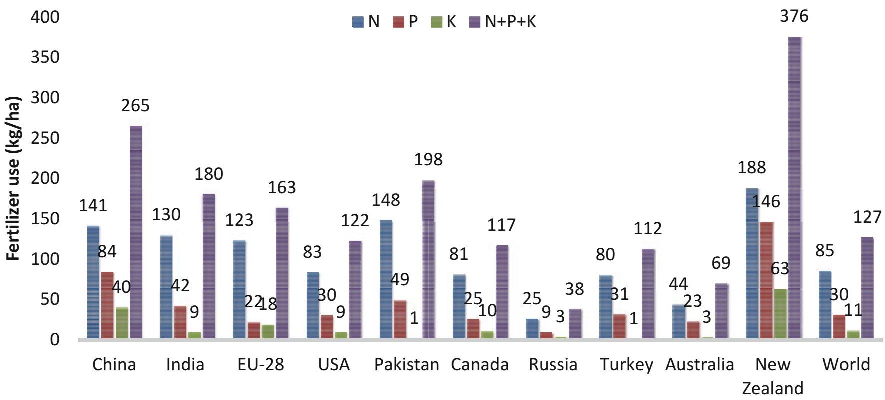

Fig. 16.2 Intensity of fertilizer consumption for wheat cultivation in selected countries (Source: Heffer 2017; FAOSTAT 2020)

fertilizers are rice (13.7 per cent share), vegetables (8.6 per cent) and fruits (7.2 per cent).

Data on fertilizer consumption for wheat production in selected countries is given in Table 16.4. Overall, about 27.8 million tonnes of fertilizers are consumed for wheat production in the world, of which N accounts for 18.6 million tonnes, P for 6.6 million tonnes and K for 2.4 million tonnes. China and India are the countries that consumed the highest quantities of fertilizers for producing wheat. China consumed about 22.9 per cent of the total fertilizers consumed by the world wheat in the year 2014, whereas India consumed about 19.7 per cent. These two countries together contribute about 40 per cent to the total N, and about 50 per cent to the total P and K fertilizer consumption of the wheat grown in the world. Interestingly, the fertilizer consumption for wheat production in China is only about 13 per cent of their total fertilizer consumption, and it about 21 per cent for India.

The total quantity of fertilizer consumed for wheat production may not be the best indicator to identify the intensive fertilizer consumers. For this purpose, the fertilizer consumption per ha of wheat grown as given in Fig. 16.2 would provide better insights. New Zealand, China, Pakistan and India follow fertilizer intensive wheat cultivation, along with EU-28 as suggested by their N + P + K figures higher than 160 kg/ha. New Zealand uses 376 kg of fertilizers per ha for wheat cultivation, and it has recorded the highest wheat yield among all the countries. However, in the global frame, it is not a very important player as far as wheat is concerned since the wheat area there is only about 0.04 Mha. We consider the consumption levels of countries like China and India to have more impact since wheat is cultivated in more than 25 Mha there. In China, about 265 kg of fertilizers are used for wheat cultivation per ha, which is constituted by 141 kg N, 84 kg P and 40 kg K. The values for India are much lower in comparison to China. While a total of 180 kg fertilizers is consumed per ha, the quantity of N used per ha is 130 kg, and that of P and K are 42 kg 9 kg per ha respectively. Pakistan, the USA, Canada and Turkey are the other countries that follow in the list. The optimal level of fertilizer use for wheat varies with regions, variety, cropping pattern and other agro-climatic and crop management practices. It is thus not practical to compare the national level fertilizer use in wheat to any single value of optimal fertilizer use to arrive at the extent of overuse or underuse. For this purpose, recommendations of regional or local agricultural research stations of organizations based on soil test and all other biophysical characteristics are more valid. However, there is no doubt that excessive fertilizer application to soil, at levels higher than the actual crop requirements, often lead to reduced net revenue for the farmers, as well as externalities to the society in the form of soil, water and air pollution (Praveen 2017).

16.7 Fertilizer Consumption for Wheat Cultivation in India

In India fertilizer usage per hectare is highest in sugarcane, followed by wheat, cotton and paddy. Paddy and wheat are the crops that receive the highest share in fertilizer subsidy (also because of the higher share in the area). These two crops together account for about half of the total subsidy distributed for fertilizers in the

Table 16.5 Crop wise fertilizer consumption in India

Crop	Fertilizer used ('000 tonnes)				Fertilizer used per ha GCA (kg/ha)	Share in fertilizer consumption (%)
	N	P	K	Total		
Paddy	4413.45	1946.71	907.93	7268.09	149.34	29.30
Wheat	3533.01	1472.32	268.56	5273.90	177.96	21.26
Jowar	333.00	165.17	49.45	547.62	87.54	2.21
Bajra	257.78	104.33	32.15	394.26	49.31	1.59
Maize	735.22	335.60	130.48	1201.31	112.23	4.84
Groundnut	157.81	130.18	50.85	338.84	102.05	1.37
Sugarcane	762.59	411.21	221.13	1394.92	319.55	5.62
Cotton	1403.81	534.21	213.86	2151.88	153.43	8.68
Total foodgrains	10494.95	4592.98	1543.30	16631.23	130.85	67.05
Total pulses	993.89	437.49	107.57	1538.95	81.85	6.20
Total oilseeds	1374.19	797.63	204.41	2376.24	92.60	9.58
Total fruits	230.87	154.34	118.24	503.45	177.90	2.03
Total vegetables	373.17	251.94	146.91	772.01	197.72	3.11
Total spices and condiments	142.10	93.03	47.17	282.31	144.07	1.14
All crops	15150.66	7051.84	2599.96	24802.47	130.71	100.00

Source: Praveen et al. (2017a)

country. Sugarcane, wheat, cotton and paddy are again the crops that benefit the most from fertilizer subsidy received per hectare crop area. The intensity of fertilizer use, and hence the incidence of subsidy however varies across the states for the same crop (Table 16.5). Paddy, wheat, sugarcane and cotton are thus the crops that benefit most from the fertilizer subsidies. The share of fertilizer cost in total operational cost is also high in these crops in major producing states. For example, fertilizer cost contributed about 17.68, 14.01 and 12.87 per cent respectively to the total operational cost of paddy in the states of Karnataka, Andhra Pradesh and Uttar Pradesh. Similarly, its share is as high as 21.87, 16.64 and 14.42 per cent respectively for wheat, sugarcane and cotton in Maharashtra (Praveen et al. 2017b

Per ha fertilizer usage in wheat crop across the states and its trend over the years is given in Table 16.6. Punjab has the highest per ha consumption of fertilizers (237 kg/ha) closely followed by Gujarat (196 kg/ha). The fertilizer use intensity in these states is higher than the global average and only behind China. A higher proportion of area under irrigation and more area under improved cultivars in Punjab is the reason for higher fertilizer use. Also, it should be noted that in all the major states, fertilizer use has registered a positive growth over the years. In Table 16.7, the decomposition of fertilizer use by nutrient is provided. One important observation can be drawn from it. There is over-reliance on Nitrogenous fertilisers, mainly at the cost of Potassic fertilizers. Studies based on field trials show that a balanced application of fertilizers would result in a better crop response to fertilizers. The response also varies with locations and other biophysical characteristics. While the application of nitrogen fertilizer alone increased the wheat yield by about 50 per cent in comparison to the control, the combined application of nitrogen and phosphorous fertilizers increased the yield by 97 per cent, and that of nitrogen and potassium by 73 per cent. More importantly, the combined application of nitrogen, phosphorous and potassium increased the wheat yield by about 137 per cent in comparison to the control (Panwar et al. 2019). It is also to be noted that the yield response aried with locations. The issue that we face however is the overuse of chemical fertilizers in few states (Mostly the green revolution belt) and the overreliance on Nitrogenous fertilizers is a cause of concern from the perspective of sustainability (Singh 2000). Part of the problem of over use of nitrogenous fertilizers is due to policy changes, which is explained in the following section.

16.8 Fertilizer Policy Landscape: India

Fertilizer is an indispensable input in Indian agriculture. However, the extensive, or rather indiscriminate, use of fertilizers also affects the health of the environment posing sustainability issues. At present, the journey of Indian agriculture has reached the juncture, where, the country needs to carefully plan the future trajectory to embrace both food security as well as environmental sustainability. The recent changes in the fertilizer sector, mostly policy-driven, targets addressing these two very important but arduous tasks.

Table 16.6 Average fertilizer consumption for wheat production in selected states (kg/ha)

Year	Bihar	Gujarat	Haryana	Madhya Pradesh	Maharashtra	Punjab	Rajasthan	Uttar Pradesh
2006–07	122	139	205	90	–	228	115	164
2007–08	117	152	207	108	–	236	123	159
2008–09	128	166	206	103	172	235	124	179
2009–10	127	186	199	101	184	239	131	182
2010–11	126	179	203	105	192	245	133	182
2011–12	120	177	203	104	157	243	122	164
2012–13	125	170	191	108	153	240	120	168
2013–14	145	187	202	100	192	251	131	174
2014–15	150	195	147	112	138	247	142	179
2015–16	142	202	195	116	139	245	141	176
2016–17	137	196	191	128	168	237	147	179
CAGR	1.1	3.5	−0.7	3.6	−0.3	0.4	2.5	0.9

Source: Directorate of Economics and Statistics 2020 (Cost of cultivation data)

Table 16.7 Average NPK consumption for wheat production in selected states (kg/ha)

State	N	P	K
Bihar	86	45	6
Gujarat	120	44	3
Haryana	132	55	1
Madhya Pradesh	80	41	1
Punjab	158	61	1
Rajasthan	97	46	1
Uttar Pradesh	116	60	1
Source: Directorate of Economics and Statistics 2020 (Cost of cultivation data)			

India is the second-largest consumer of fertilizers in the world (FAI 2021). Fertilizer use continues to increase in the country owing to better availability powered by the combination of domestic production and imports. The performance of the fertilizer sector in recent years needs to be seen from different dimensions. Total consumption of fertilizer nutrients increased from 26.5 million tonnes in 2017–18 to 27.2 million tonnes in 2018–19 9 (2.6 per cent growth). Though the increased demand for fertilizers was met by the sector, the indigenous production of urea and DAP got reduced during the period. To compensate for this, the imports of these fertilizer products were increased by 25 and 55 per cent respectively in 2018–19 compared to the preceding year. While nitrogen and phosphate consumption experienced an increase, farmers repudiated potash during the period resulting in widening of NPK use ratio to 7.1:2.7:1. Though reduced availability of potash is not the actual cause for its lesser consumption, continuous monitoring of the movement of fertilizer products do different parts of the country is required to correct imbalances. This is important since tracking the movement and supply of fertilizers is now made much easier due to mFMS system (web-based tracking system).

In India, the government implements several reforms from time to time to regulate fertilizer use in agriculture. While the former policies were intended to increase fertilizer production and consumption, most of the recent policies targets limit the fertilizer use to the required level and keep the NPK balance at the desired levels. Realising the importance of the balanced application of fertilizer nutrients was the crux of several key policies related to fertilizers in the recent period. While the recommended NPK ratio for the country is 4:2:1, at present it is 7.1:2.7:1. Besides, there is a wide disparity in nutrient use across states. To correct the multi-nutrient deficiency inflicted due to the improper use of fertilizers, the government started promoting customised as well as fortified and coated fertilizers in 2008. This was followed by the Nutrient Based Subsidy (NBS) policy for P and K fertilizers in 2010. As per the NBS, the subsidy amount will be fixed for nutrients annually, which will be distributed based on the nutrient content in each grade of fertilizers. After the implementation of the Nutrient Based subsidy, the availability of P and K fertilizers have always been over demand. The importance of micro-nutrients is also recognised in the NBS, as they attract additional subsidies. Another policy that is intended to modify the approach of farmers towards fertilizer application is the Soil Health Card (SHC) Scheme of 2015. The scheme intends to distribute soil health cards, to individual farmers, that describe the nutrient status of their agricultural plots, along with the best nutrient recommendation. However, research has shown that soil test information alone may not be enough to change the fertilizer application practices by the farmers. Soil test information may not make an impact unless the farmers are made aware of its importance and are trained properly to use it. Simplifying the SHC is crucial for better comprehension by farmers, and they also need to be engaged regarding the use of SHC by repeated contact by the extension system over telephones or personal visits for the intended impact (Kishore et al. 2021).

To increase the nitrogen use efficiency, the government chose for compulsory neem coating of urea, both produced as well as imported ones. Since more than 80 per cent of the nitrogen applied to Indian soils is through urea, this policy is expected to deliver dual benefits of improved nitrogen use efficiency and reduced illegal diversion of urea for industrial purposes. Moving ahead in the direction of correcting the nutrient imbalance, the size of the urea bags were reduced from 50 kilograms to 45. The country is expecting positive results from all these well thought out policies shortly.

Several policy reforms are introduced by the government from time to time to ensure efficient and cost-effective delivery of fertilizers, better targeting of the subsidies and ensure soil nutrient balance. The latest among them is the DBT system for fertilizer subsidy distribution which was introduced in March 2016 on a pilot basis in 16 districts of the country. DBT is a modified subsidy payment system, where fertilizer companies will be paid subsidy only after retailers have sold fertilizer to farmers/buyers after the identification of beneficiaries using Aadhar card or any other relevant identification proof, through Point of Sale (PoS) machines. The scheme was later rolled out pan India in March 2018. Though the original design of the scheme includes linking the farmers' landholding details and soil health readings to provide the recommended fertilizers, operational difficulties compelled to withhold this. However as the DBT moves to later phases when the farmer gets the subsidy directly in their accounts, such linkages will be beneficial to ensure customised nutrient use at the individual farmer level. Retailers are the key actors in DBT since the scheme is implemented with huge additional responsibilities for them. To compensate for this, the retailers' margin is also increased. Though the scheme is still in its initial years of operation, it is a huge step by the government that has changed the roles of key actors in the fertilizer supply chain.

India is the largest importer of fertilizers as well as raw materials. The global market trends depend immensely on Indian imports. The flip side of this is that it positions the country in a vulnerable situation concerning the dependence on key fertilizer products. The government has been working on this issue and have recently sanctioned a few new urea plants, a step to reach self-sufficiency in urea production. About eight million tonnes increase in urea production capacity is expected soon. If the country succeeds in this, it can be self-sufficient in urea, contingent upon the fact that all the existing units produce efficiently. In the case of P and K fertilizers, the capacity of the industry is sufficient to meet domestic demand, however, capacity utilization is the concern. The dependence of the units on imported raw materials makes them vulnerable to price fluctuations and other market uncertainties. Though complete self-reliance may not be the best way forward for India in fertilizers, cooperative and joint venture projects are now increasingly established to insulate the country from the issues mentioned above.

Increasing emphasis on organic and biofertilizers by the government is another big step in the road to a sustainable future. The government is attempting to promote the use of these products in the country through a host of measures: creating awareness about biofertilizers through demonstrations conducted by vast agri-extension network, financial support to the biofertilizer producing units, subsidized prices, and promotional schemes for encouraging direct production by the public, cooperative and research institutions for distribution. Despite the efforts, the Indian biofertilizer market is still in the infant stage since its demand has not expanded as desired. The uncertainty in the performance of biofertilizers and the nature of benefit which is spread over long periods are affecting the growth of the biofertilizer sector. The setting up of the National Centre for Organic farming, to coordinate the development of organic and biofertilizer segments and popularise these among the farmers is a welcome step.

The biggest change in the Indian fertilizer sector seems to be the fact that all the actors, be it the government, industry, or the farmers, all are now aware that the maximum benefit for agriculture can be derived if the soil is provided nutrients of all nature: inorganic, organic and biofertilizer. The majority of fertilizer policies, implemented in the line of the green revolution, were skewed towards increasing the volume of fertilizers, to achieve higher production, are now being re-assessed. Contemporary policies consider environmental sustainability and balanced nutrient application with equal weightage as that of food production.

16.9 Policy-Based Attempts for Curbing Externalities of Fertilizers

Pollution due to fertilizers, especially nitrogen, is fast growing as a threat to humans and the environment (Fowler et al. 2015). The problem with N pollution is that multiple sectors and activities are involved in the N cycle and hence inventory management for assessing the extent of emission itself is difficult. However, several policies are implemented across the world that seeks a balanced level of N in the system and bring down nitrogen pollution. To be more specific about 2726 policies are identified from different countries that deals with N. Among these, 942 policies are identified to be regulating N in the agriculture sector. However, not all are implemented to reduce N, some policies are pro N that attempts to increase N use. Such policies need to be visited in terms of the context and regions that were implemented and should be reassessed continuously to find out the point of exit. However, governments may find the policies that support N for example subsidies, very difficult to remove due to political and social pressures (Kanter et al. 2020).

Most policies dealing with agricultural N pollution attempt to alter the farmers' behaviour which is very difficult (Reimer et al. 2018). Waste, industry, transport and energy are the other sectors that attracted policy-based efforts from various governments. Most of these policies are regulatory policies, and they focus mainly to protect water from getting polluted. The policies protecting air, ecosystems, climate and soils also have attracted the attention of various governments.

Europe leads the way in curbing N pollution with about 971 policies, and Asia, North America and Africa follow it in the list (Kanter et al. 2020). The Gothenburg Protocol signed in 1999 to curb long-range transboundary transport of air pollutants in Europe is one of the important steps in the regime, following which EU implemented the National NH_3 Emission Ceilings directive in 2001 (EEA 2019). EU has been successful in decreasing the fertilizer consumption, which is clear from the fact that between 1987 and 2007, their fertilizer consumption was reduced by almost 56 per cent. Denmark is one country that took an early step way back in the year 1987 in the form of the Nitrate Directive that mandates the adoption of Best Nitrogen Management Practices in agriculture (European Commission 2010).

A Contrasting visual can be seen in the case of China, where high N input, low technological level and poor management are the characteristics of the agriculture sector that place it in the hotspot of the world (Zhou et al. 2016). About one-third of the total N fertilizer consumed in the world is applied to the croplands of China (9 per cent of world crop area), mostly in the form of urea (Gu et al. 2015). The nitrogen use efficiency in the majority of their cropland is low and is only about 40 per cent, which compels the farmers to overuse N so that the fertilizer required to maintain the desired yield level for the crop is ensured. The extent of N overuse can be detected from the fact that a typical wheat-corn cropping system in North China Plain use about 500–600 kg N per ha per year (Zhang et al. 2017). Studies suggest that in China about 30–60 per cent reduction in the N fertilizers applied to wheat can be achieved without affecting the yield (Ju et al. 2009). The earlier policies of the government in the form of subsidies and other means of supports ensured a good growth of the fertilizer industry, but very low prices of fertilizers lead to its overuse by farmers (Li et al. 2013). The government's attempt to control agricultural pollution is mainly through the approach of soil testing and 4R nutrient stewardship (Gu et al. 2020). The concept of 4R nutrient stewardship involves the application of nutrients from the right source, at the right rate, at the right time and in right place by considering the crop requirements and agro-climatic characteristics (Johnston and Bruulsema 2014).

In the USA, the United States Environmental Protection Agency (EPA) leads the fight against nutrient pollution. Agricultural non-point source pollution is the major water pollutant in the country as reported in the National Water Quality Inventory. EPA promotes collaborative approaches involving stakeholders to tackle the issue. EPA monitors different regulatory policies and programs that ensure safe drinking water, identify polluted water bodies, establishing discharge limits and monitoring, create awareness in the general public, and popularize scientific findings that are useful for stakeholders. EPA works with USDA and other organizations to manage the nutrient outflow from their respective sectors. It also finances nutrient reduction activities in the form of grants to the states to manage nutrient pollution.

Nutrients are necessary for plant growth and when we attempt to grow crops in agricultural systems that are deficient in nutrients, the chemical fertilizers come into help there. N is the key macronutrient that limits crop growth. N fertilizer application in agriculture has rapidly increased since the green revolution. Though N fertilizers have helped increase the yield, there is an optimum beyond which the added fertilizer N may not be manifested in the form of higher yields. This is because the crop may not be able to use the abundant N applied through chemical fertilizers due to limiting factors like their innate photosynthetic capacity and genetic potential. Educating the farmers about this non-linear relationship between N fertilizer and crop yield is crucial. From the sustainability point of view, achieving more yield with lesser amounts of fertilizers is the best state if achieved. Higher use efficiency of fertilizers is one strategy with which yield can be improved without adding more physical quantity of fertilizers. Efficient fertilizer management is crucial for both, better wheat production and minimum environmental damage. Timing and method of fertilizer application are bound to have a direct effect on fertilizer use efficiency, depending on the soil characteristics. Nitrogen fertilizer application as topdressing could enhance the nitrogen use efficiency and reduce losses to the environment if applied between tillering and stem elongation stages of durum wheat (Lopez-Bellido et al. 2006). Point injection of nitrogen, 10 cm deep and 20 cm intervals, has proved to be beneficial for enhanced nitrogen uptake by wheat in competition with weeds (Blackshaw et al. 2002).

Farmers should be educated about the benefits of applying the right kind and quantity of fertilizers and the ill effects of indiscriminate application. For this mass, efforts need to be initiated by the governments. Measures to link fertilizer use with the soil health status of individual plots if taken will be huge progress towards the goal. Availability of customised and fortified fertilizers should be ensured as per the requirement of the area. Use of fertilizers that delay the nitrogen release to the soil, reduce the nitrate leaching and eutrophication and check the diversion of urea to some extent. More of such speciality fertilizers, for example, slow-release fertilizers like sulphur coated urea, urea deep placement and other area and crop-specific and water-soluble fertilizers addressing the secondary and micronutrient deficiencies of the soil should be promoted. Measures to promote bio-fertilizers is also very important in building a sustainable system. Despite the proven benefits of using bio-fertilizers, its sales are not picking up in most countries. One needs to go deeper into this issue to understand whether the problem exists on the demand side or supply to make a positive change.

Several long-term studies on Best Nutrient Management Practices (BNMP) taken up in the USA and UK have reported that the fertilizer applied to crops like rice, wheat, maize and barley can be reduced following the BNMP. Most farmers currently follow the strategy of economically optimum level of fertilizer application that attempts to maximum economic gains after considering the fertilizer prices. However, in the current context, environmental and economic optimum fertilizer rate can play the trick by internalizing the environmental costs of excessive fertilizer application (Good and Beatty 2011). The issue however is that the policies across the globe that depend only on the farmers to manage the nutrient overflow to the crop production systems have not given the intended results. The governments and policymakers need to understand that managing nutrient pollution is a very difficult task, and to make any progress the cooperation of all the key players is important. Along with farmers, the fertilizer industry, government, extension agencies and agricultural research organizations have crucial roles to play in ensuring the balance.

16.10 Conclusion

The importance of wheat as food to the world is unquestionable. The growth in wheat production in the past is driven by new input responsive varieties and intensive cultivation practices. With questions of sustainability and climate change being more important concerns than production enhancement, the input use in agriculture in general needs a relook. Wheat being an important food crop, the challenge is to sustain the production and decrease the negative externalities of input use and resource depletion. We have presented here a brief overview of fertilizer use in major wheat production regions of the world. The case of India, a major wheat producer is also highlighted. The fertilizer use intensity in wheat cultivation varies due to the production system characteristics, agroclimatic regions and the varietal requirements. However, it is important to acknowledge that fertilizer use efficiency is the key, and hence measures need to be taken to make the fertilizers available to the crop at the right time and in the right form. The use of precision agriculture techniques that help to apply only the required fertilizer quantities to crops and the use of nanoformulations of fertilizers are necessities of the future considering the sustainability issues that we face. Such innovative practices will ensure a reduction in nutrient outflow to the environment in the form of leaching, volatilization and emissions. In this line, the recent fertilizer research on India has focused on the topics like food security, externalities of fertilizer application, the possibilities of reducing such negative effects through the conjunctive use of biofertilizers and organic fertilizers, nutrient use efficiency, and crop yield response to fertilizers. Research to recommend location-specific fertilizers based on soil quality and their nutrient absorption capacity is also stressed of late suggesting that the Indian and fertilizer policy and research expanse of the recent period, is moving in the right direction. However, research contribution by social science needs to be improved so that empirical evidence on the actual fertilization practices by farmers is brought to light for further research by the other subject groups. The fight against nutrient pollution is complex and requires continuous and sustained efforts and the countries must learn from mutual experiences.

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Technical Efficiency in Indian Wheat Production: Regional Trends and Way Forward

17

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17.1 Introduction

Ensuring adequate and stable supply of food and nutrition has remained the foremost priority of the nation. Globally, cereals are the prime source of nutrition as well as calorie intake and thereby represent foundation to human system, particularly in developing countries (Cassman 1999; Alexandratos and Bruinsma, 2012; Shiferaw et al. 2011). Among cereals, wheat is one of the leading staple food crop grown around the world which is cultivated in more than 250 million hectares and have 765.4 million tonnes of production (Statista 2020). It is a major source of income for millions of small and marginal landholders in low and middle income countries (Wheat initiative 2015). More than half of the global wheat is produced by China, India, Russia, U.S.A, Ukraine, Canada, and Pakistan. According CGIAR, it is consumed by 2.5 billion people around the world and provides about 20 percent of daily protein and calorie intake.

India has second-largest arable land in the world, with 20 agro-ecological regions and 156.46 million hectares of area under cultivation (DES 2019). Hence, agriculture plays a pivotal role in Indian economy by being a major source of livelihood for more than two-third of rural households (Kumar 2005). Globally, India is a powerhouse for wheat cultivation, holds largest cultivated area and ranks second in wheat production in the world (after China). Wheat is the second leading staple food crop of the country, and cultivated across diverse climatic conditions. It is an important daily diet for millions of people, provides food and nutrition security especially in

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northern and north-western regions of the country (Ramadas et al. 2019a; Sharma and Ramadas 2016).

The 'Green Revolution' launched during 1960's led to massive increase in wheat production and helped India to attain self-reliance in food production. The area, production and productivity of wheat has significantly increased by several folds compared to pre-green revolution. Due to comparative geographical advantage and rapid adoption of HYV of wheat, states like Haryana, Punjab, UP and MP became leading wheat producing states in the country (Pingali et al. 2019). In addition, wheat production and protection technologies also helped to minimize the instability in food grain production of India (Sharma et al. 2014).

India has witnessed significant improvements in productivity of cereals especially during post green revolution through adoption of various input intensive technologies. Consequently, at national level, yield of wheat has reached at its highest record of 3507 kg/ha during 2018–19 (DES 2019). However, recently, several studies indicated that wheat yield has been stagnated in most of the traditional wheat growing regions and thereby pose a hurdles in achieving additional production (Ray et al. 2012; Sharma et al. 2014; Balaji 2018). Land degradation, heat stress, scarcity of land and water resources, depletion of soil fertility, plateauing of yield in current varieties and combination of several other factors contributed to reduction/stagnation in wheat yield (Licker et al. 2010; Peng et al. 2004; Ladha et al. 2003).

17.2 Trend in Wheat Yield

In India, wheat is a rabi season crop sown in winters during first fortnight of November and harvested in spring season i.e. April to May. Table 17.1 furnishes the temporal and spatial scenario in wheat yield from 2001–02 to 2018–19. It is clear that at national level, yield has increased significantly from about 2.75 tonnes/ha in 2001–02 to 3.37 tonnes/ha in 2018–19 with a rate of 22.47 percent. Decadal comparison in yield shows variation over different period of time. The yield has increased by 5.90 percent (0.16 tonne/ha) during 2001–02 to 2010–11 and 15.64 percent (0.46 tonne/ha) in 2011–12 to 2018–19. The states also followed similar pattern with different magnitude and confirms the regional variations in yield. Surprisingly, Madhya Pradesh, Uttarakhand, Himachal Pradesh and Bihar performed better in terms productivity than traditional wheat growing states viz., Punjab and Haryana. The productivity jump is caused mainly by adoption of HYVs and good agricultural practices along with other inputs.

The historical trends in wheat productivity across major Indian states shows regional disparity in wheat yield (Fig. 17.1). Surprisingly, the productivity of wheat is improving in non-traditional wheat growing regions having only 23 percent share (five million ha) of total wheat area and 16.6 percent share of wheat production of the country. However, the traditional wheat growing states (Punjab, Haryana, Uttar Pradesh, Rajasthan, Bihar, Jharkhand, Odisha, Maharashtra, Uttarakhand and Jammu & Kashmir) are experiencing stagnation in wheat yield. These states

Table 17.1 Trend in wheat yield across major wheat producing states (2001–02 to 2018–19)

State	Yield (kg/ha)*			Percent change (%)		
	2001–02	2010–11	2018–19	2001–02 to 2010–11	2011–12 to 2018–19	2001–02 to 2018–19
Bihar	2132	2025	2777	−5.03	37.11	30.22
Gujarat	2273	2737	2890	20.40	5.58	27.12
Haryana	4125	4409	4617	6.90	4.71	11.94
Himachal Pradesh	1335	1326	1859	−0.68	40.20	39.25
Jharkhand	1695	1640	1993	−3.25	21.50	17.55
Madhya Pradesh	1651	1816	2987	9.95	64.54	80.90
Punjab	4597	4487	4990	−2.39	11.20	8.54
Rajasthan	2578	3073	3337	19.18	8.59	29.41
Uttar Pradesh	2747	2987	3271	8.72	9.52	19.06
Uttarakhand	1909	2152	2749	12.75	27.69	43.97
India	2749	2912	3367	5.90	15.64	22.47

* Triennium Ending Average

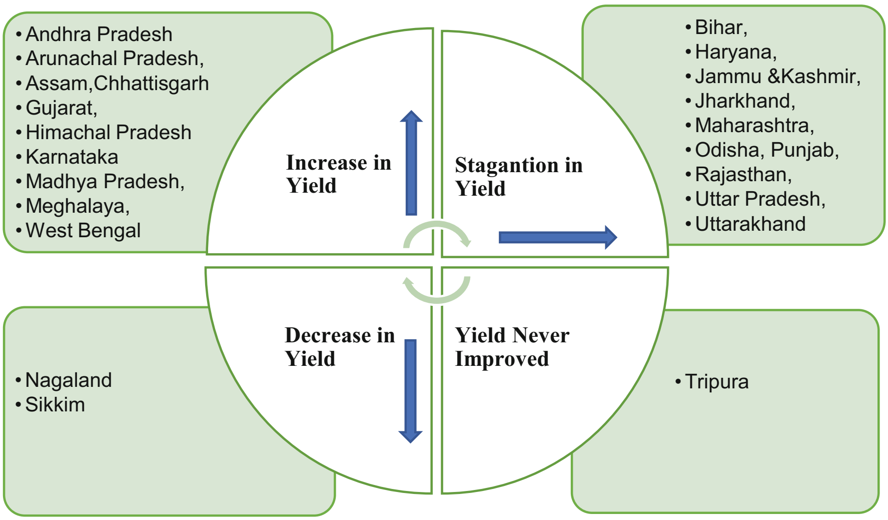

Fig. 17.1 Typology in wheat productivity of major Indian states (Modified and Adapted from Madhukar et al. 2020)

constitute more than three-fourth of total wheat area and produce more than 80 per cent of wheat in the country. It is a serious concern that major wheat producing states of the country are now showing decreasing/stagnating trends in yield (Madhukar et al. 2020).

17.3 Trend in Cost of Production Wheat in India

Despite of having a rising wheat productivity, cost of production of wheat in India is also increasing over the years (Fig. 17.2). Among other inputs, human labour contributes to the highest share in the cost of production of wheat (24%) followed by machine labour (13%), fertilizer and manure (8%), insecticides (7%), seed (6%), animal labour (3%) and irrigation charges (1%) (Fig. 17.3). Indiscriminate use of inputs/inefficiency in production and rise in input costs nullifies the gain in productivity and thereby increases the cost of production. One way of lowering the cost of production is by increasing the efficiency in production of output. This can be

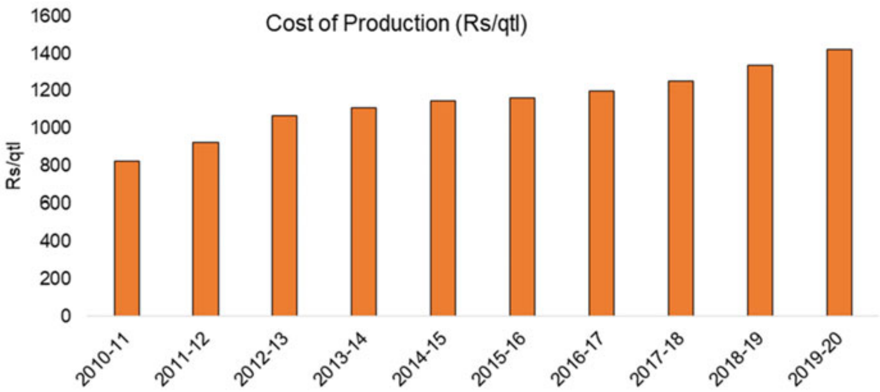

Fig. 17.2 Trend in cost of production of Wheat in India (Source: MoA&FW, GoI)

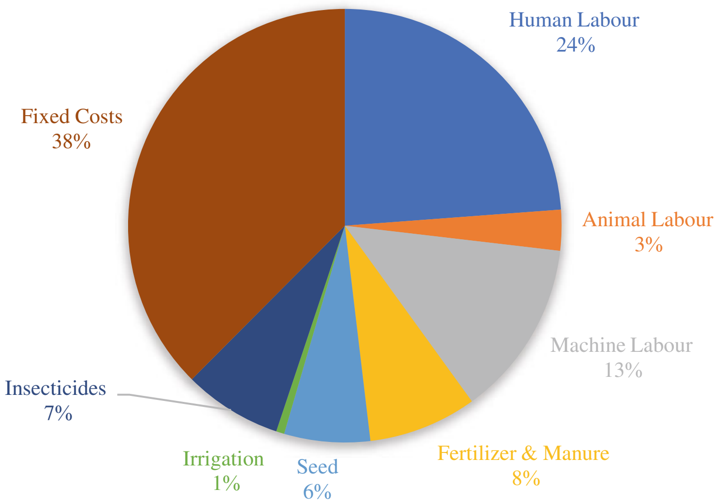

Fig. 17.3 Share of inputs in total cost of cultivation of Wheat (2016–17)

attained either by producing the same output with lesser inputs or by producing more output with same amount of resources.

17.4 Efficiency in Wheat Production

Historically it is well known fact that fostering agricultural productivity paves the way for development of other sectors in the economy as agriculture supplies key of inputs to other industries. Agriculture became cutting-edge for successful industrial revolution and pre-requisite in the process of development in many developed countries. Krueger et al. (1991) and Stern (1989) established relation that high agricultural productivity is one of the strong driver for successful industrialization for the many economies whereas countries with low level of productivity became relative less successful in the industrialization. Hence, agricultural productivity plays a pivotal role in the structural transformation and development of the economy (Morris and Adelman 1988).

Agricultural production can be increased by two ways, either through generation of innovative technology and its successful adoption or alternatively by efficient use of existing resources/technology. Thus, efficiency plays a pivotal role by guiding the optimum allocation of scarce resources (Farrell 1957). Technical efficiency is defined as the ability of the firm to produce optimum/maximum level of output with a given set of inputs (Farrell 1957). In absolute terms, efficiency of a farm is measured as difference between actual output and maximum potential output from the given set of resources. Farm productivity (yield/ha) is often considered as the simplest way to represent efficiency in agricultural production. However, this holds true only under the assumption that farmer is always technically efficient in producing output (Grosskopf 2003; Fare et al. 1989). Furthermore, productivity gains are not entirely due to improvement in efficiency because productivity depends on both production technology (quantity & quality of inputs) and technical efficiency (input combination used in production). To quote with an example, the gains in productivity during the period 1961–2007 in Latin America and the Caribbean was mainly because of technological change, whereas efficiency change was negative during the same period (Ludena 2010).

17.4.1 Status of Efficiency in Wheat Production in South Asia

Wheat is the one of the prime staple food crop of South Asian countries and thereby plays a critical role in food security of the region (Joshi et al. 2007). In this region, wheat is cultivated in more than 47 million hectares which is about 22 per cent of global wheat area with a production of 146 million tonnes i.e. 20 per cent of world's wheat (FAO 2018). However, with the growing demand for wheat there is a big challenge to accelerate the wheat production with the same set of resources.

In this context, several studies have been focused to measure the technical efficiency in wheat production in South Asia. Ahmad et al. (2002) estimated the average technical efficiency of wheat farmers of Pakistan using farm level data. It was observed that farmers are operating below production frontier and there is a significant scope to increase efficiency (32%). Tavva et al. (2017) analysed the efficiency in wheat production of Afghanistan and found that about 33 percent additional output of wheat can be produced in the short run with the same bundle of inputs. Similarly, in Bangladesh, Hassan and Islam (2012) estimated technical efficiency in wheat production by using farm level cross sectional data. Study highlighted that about 16 percent additional yield can be obtained by using the existing level of resources and technology in the country. In India, numerous studies have been carried at farm and regional level to measure technical efficiency in wheat production. Kaur et al. (2010) estimated that about 13 percent additional wheat can be produced in Punjab region by using same level of resources. Further, study also highlighted that age, education, farm experience and irrigation were crucial factors in determining the technical efficiency.

Overall, South Asian countries still have scope to increase the wheat productivity by improving technical efficiency by using current level of technology and resource use.

17.4.2 Technical Efficiency and Total Factor Productivity (TFP) in Indian Wheat Production

In addition to generation of technologies and improving efficiency, another way of achieving an increase in production is through increasing the total factor productivity which is simply a ratio of total output to total inputs. When all inputs in the production process are accounted for, Total Factor Productivity (TFP) growth can be thought of as the amount of growth in real output that is not explained by growth in inputs. It includes both change in efficiency as well as technical change. The change in total factor productivity was estimated using a non-parametric Malmquist TFP index approach. The Malmquist TFP index measures the maximum level of outputs that can be produced using a given level of inputs and the given production technology relative to the observed level of outputs. The trend in the Malmquist TFP index were estimated for the period 2001 to 2016 using the cost of cultivation summary data of wheat for twelve major wheat growing states of India, viz. Bihar, Chhattisgarh, Jharkhand, Haryana, Himachal Pradesh, Madhya Pradesh, Punjab, Rajasthan, Uttar Pradesh, Uttarakhand and West Bengal.

The output and inputs are used in physical quantities to avoid the variations in price information: Yield (in kg/ha), seeds (in kg/ha), human Labour (in hrs/ha), fertiliser (in kg/ha) and real cost per hectare for irrigation and machine labour (Table 17.2). The real cost of irrigation and machine is obtained by deflating them with price indices of electricity and tractor, respectively.

Table 17.3 depicts the growth in inputs use and output in wheat production for major wheat producing states of India for the period 2001–02 to 2016–17. There was a drastic decline in the human labour use in the wheat production during this period which range from −0.7 percent in Himachal Pradesh to −3.8 percent in Gujarat.

Table 17.2 Summary of output and input use in wheat production (2001-02 to 2016-17)

State	Yield (kg/ha)	Seed (kg/ha)	Fertiliser (kg/ha)	Human labour (man hours/ha)	Machine labour (Rs/ha)	Irrigation (Rs/ha)
Bihar	2453	115	128	417	3780	2627
Chhattisgarh	1395	105	88	328	1986	2598
Gujarat	3251	157	166	466	3877	3963
Haryana	4267	116	200	293	6298	3153
Himachal Pradesh	1373	125	60	271	3147	296
Jharkhand	1536	116	101	390	2190	1778
Madhya Pradesh	2654	115	102	316	3792	2639
Punjab	4428	105	237	174	6421	545
Rajasthan	3673	153	124	503	3980	3902
Uttar Pradesh	3299	145	166	444	4987	3701
Uttarakhand	2808	122	85	428	1425	890
West Bengal	2442	124	174	751	1721	3281

Table 17.3 Yield and inputs growth (% per year) in wheat production across states (2001–02 to 2016–17)

State	Yield (kg/ha)	Seed (kg/ha)	Fertiliser (kg/ha)	Human labour (man hrs/ha)	Machine labour (Rs/ha)	Irrigation (Rs/ha)
Bihar	2.5	−0.1	0.5	−1.8	4.5	5.3
Chhattisgarh	4.9	0.2	−2.8	−3.1	20.5	6.5
Gujarat	1.3	0.4	2.9	−3.8	8.9	1.7
Haryana	1.6	−0.6	0.3	−1.2	5.1	5.7
Himachal	4.4	0.1	3.1	−0.7	10.4	100.2
Jharkhand	6.3	−0.6	4.2	−1.3	0.8	12.2
Madhya Pradesh	5.6	−0.2	3.7	−1.0	10.4	5
Punjab	1.0	0.3	0.4	−3.5	4.1	5.2
Rajasthan	1.6	0.2	2.6	−1.1	6.5	4.0
Uttar Pradesh	2.3	0.3	1.9	−0.8	5.3	9.5
Uttarakhand	4.5	0.6	10.3	−0.9	6.4	26.4
West Bengal	2.9	1.7	0.3	−2.6	17.8	−0.1

Clearly, application of chemical fertilizer has increased in all the major wheat growing states except in Chhattisgarh (−2.8 percent). Bihar, Haryana, MP and Jharkhand have seen a decline in seed use while West Bengal showed maximum growth in seed use (1.7 percent). The maximum growth in chemical fertilizer was observed in Uttarakhand (10.3 percent) followed by Jharkhand (4.2 percent) and

Himachal Pradesh (3.1 percent). There is a substantial improvement in the use of machine labour and irrigation in wheat production during this period. Maximum growth of machine labour and irrigation was found in Chhattisgarh (20.5 percent) and Himachal Pradesh (100.2 percent), respectively. Though usage of human labour has declined but it still constitutes the largest share in cost of cultivation in wheat crop. Rapid increase in usage of farm machineries in wheat cultivation led to gradually decline both human and animal labour demand for farm operations (Singh 2006). Further, evidences show that as the level of mechanization increases in wheat, cost of production tend to decline due increase in productivity (Singh 2006).

Trends in technical efficiency in wheat production across major wheat producing states of India is depicted in Table 17.4. The average technical efficiency in wheat production in India was about 85.3 per cent during 2001–02 to 2016–17 indicating about 14.7 per cent additional yield can be produced with the same level of technology and resources. Existence of regional disparity in input usage, productivity and other factors significantly influence the level of efficiency in wheat production. It is clear that traditional wheat producing states viz., Punjab and Haryana are operating at production frontier line with the efficiency of 100 per cent and 98.5 per cent respectively. Use of modern technologies and adoption of innovative production methods led to increase in efficiency and contributed to reaching the plateau in recent years. Thus, there is a limited/less scope to increase in the productivity of wheat in these states. Surprisingly, Uttarakhand is also attained highest technical efficiency in wheat production thereby very limited opportunity to increase wheat production by increasing resource use efficiency. Similarly, performance of Rajasthan and West Bengal states are also better in terms of technical efficiency and operating near to production frontier with 95.3 percent and 91.4 per cent, respectively. Though Uttar Pradesh is the leading wheat producer in the country but still has scope to increase about 23 per cent of additional production of wheat through optimum usage of available inputs and technologies.

The opportunity to enhance wheat production through optimum utilization of resources is mainly reposes with the minor wheat producing states. About, 41.3 per cent inefficiency was estimated in wheat production in the state of Jharkhand, followed by Chhattisgarh (31.6%) and Bihar (27.8%) showing that more output can be produced by using current level of resources. Similarly, Ramadas et al. (2019b) also estimated farm level technical efficiency in Bihar using stochastic frontier function and advocated region –specific package of practices and optimum utilization of inputs (quality seeds and fertilizer) to increase the additional wheat production in the state.

The movements of efficiency change, technical change and TFP change in wheat production in India from 2001 to 2016 show that the movements of TFP change were mainly linked with the movement of the technical progress than with the efficiency change (Fig. 17.4).

The annual change in the index of Total Factor Productivity (TFP change) in wheat production was about 2.9 per cent in during 1982–83 to 1999–2000 (Table 17.5). However, the mean TFP change was declined to −0.2 per cent during

Table 17.4 Technical efficiency in wheat production across states during 2001–02 to 2016–17

States	Jharkhand	Uttarakhand	Chhattisgarh	West Bengal	Bihar	Gujarat	Haryana	Himachal Pradesh	Madhya Pradesh	Punjab	Rajasthan	Uttar Pradesh	Mean
2001	40.3	100	91.4	100	69.4	88.4	100	100	81	100	100	83.6	87.8
2002	86.6	100	73.1	100	73.2	85.4	100	100	76.1	100	100	85	90
2003	49.7	100	57.3	100	71.5	84.6	100	100	94.6	100	96.4	90.1	87
2004	48	100	50.8	100	74.9	84.8	98.2	81.7	89.1	100	100	75.3	83.6
2005	41.6	100	47.3	100	60.1	92.9	92.9	100	75.3	100	95.5	72.1	81.5
2006	37.1	100	51.9	100	64.3	79.8	95.1	94.7	83.4	100	100	76.8	81.9
2007	33.1	100	50.4	100	71.1	86.8	92.2	67.2	75.7	100	83.8	75.1	77.9
2008	41	100	56.5	100	68.8	70.2	100	75.4	79	100	100	70.7	80.1
2009	42.2	100	49.4	100	69.9	78.7	100	72.3	95.5	100	93	75.7	81.4
2010	46.3	100	74.4	79.7	76.2	82	100	97.5	95	100	100	78.1	85.8
2011	100	100	81.2	94.1	71.3	87.6	100	100	100	100	100	83.3	93.1
2012	100	100	65.3	89.7	80.2	71.2	96.8	100	100	100	100	76.2	89.9
2013	100	100	46.1	96.8	78.4	86.2	100	100	100	100	100	76.4	90.3
2014	61.3	100	100	86.4	78.6	73.4	100	100	100	100	91.2	63.7	87.9
2015	55.8	100	100	55.7	71.6	64.8	100	91.5	93.5	100	86.1	69.1	82.3
2016	56.6	100	100	60.3	75.4	66.1	100	100	93.7	100	79.4	72	83.6
Mean	58.7	100	68.4	91.4	72.2	80.2	98.5	92.5	89.5	100	95.3	76.5	85.3

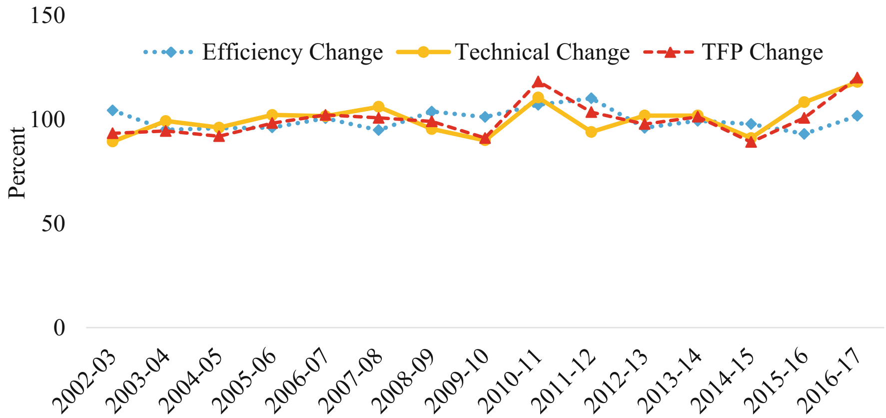

Fig. 17.4 Year-wise movement of change in technical efficiency change, technical change and TFP Indices of wheat production in India (2001–02 to 2016–17)

Table 17.5 Malmquist indices for wheat production (1982–82 to 1999–2000)[a]

	Malmquist Index (per cent)		
States	Efficiency change	Technical change	TFP change
Rajasthan	100.0	101.7	101.7
Madhya Pradesh	100.0	96.8	96.8
Uttar Pradesh	100.7	99.7	100.4
Haryana	100.0	104.6	104.6
Punjab	100.0	111.4	111.4
India	100.1	102.7	102.9
Per annum change (%)	0.1	2.7	2.9

[a]Adopted from Bhushan (2005)

2001–2016 (Table 17.6). The mean change in technical progress was 2.7 per cent during 1982–83 to 1999–2000 but declined to the tune of 0.1 percent per year in the later period. Similarly, there a change of 0.1 percent in the mean technical efficiency during1982–83 to 1999–2000 but it later declined to −0.3 per cent.

During the period 1982–83 to 1999–2000, TFP growth was reasonably higher in Punjab (11.4%), followed by Haryana (4.6%) compared to Rajasthan (1.7%) and Uttar Pradesh (0.4%). A negative growth of −3.2 per cent was recorded in Madhya Pradesh during that period. While the growth of TFP during 1980s and 1990s was predominantly explained by technical progress of these states, the technical efficiency showed no growth except for Uttar Pradesh during the period.

In the recent years (2001 onwards), the pace of TFP growth have slackened in the technologically advanced states viz. Punjab (0.3%), Haryana (0.6%) and Uttar Pradesh (0.4%). The negative TFP growth was observed in Himachal Pradesh (7.7%), West Bengal (−6%), Gujarat (−0.7%) and Rajasthan (−0.2%). The major reason of this negative growth was poor technical advantage in Himachal Pradesh

Table 17.6 Malmquist indices for wheat production (2001–02 to 2016–17)

States	Malmquist index (per cent)		
	Efficiency change	Technical change	TFP change
Bihar	100.6	100.6	101.1
Chhattisgarh	100.6	101.8	102.4
Gujarat	98.1	101.2	99.3
Haryana	100.0	100.6	100.6
Himachal	100.0	92.3	92.3
Jharkhand	102.3	101.7	104.0
Madhya Pradesh	101.0	102.0	103.0
Punjab	100.0	100.3	100.3
Rajasthan	98.5	101.3	99.8
Uttar Pradesh	99.0	101.4	100.4
Uttarakhand	100.0	101.1	101.1
West Bengal	96.7	97.2	94.0
India	99.7	100.1	99.8
Per annum change (%)	−0.3	0.1	−0.2

while negative growth in efficiency combined with poor technical change caused negative TFP growth in West Bengal (Table 17.5). Highest growth in TFP was found in Jharkhand (4%) followed by Madhya Pradesh (3%), Chhattisgarh (2.4%), Bihar (1.1%) and Uttarakhand (1.1%) which is explained by increment in technical efficiency as well as increasing technological change in wheat production in these states.

The per year efficiency change in wheat production during 2001 to 2016 was negative for West Bengal (−3.3%), Gujarat (−1.9%), Rajasthan (−1.5%) and Uttar Pradesh (−1%) while it was stagnant in Haryana, Punjab, Uttarakhand and Himachal Pradesh. A positive efficiency growth was seen in Jharkhand, Madhya Pradesh, Chhattisgarh and Bihar which was the predominant facilitator positive growth in TFP of wheat rather than technological advancement.

17.5 Determinants of Efficiency in Wheat Production

It is important to look into the major factors affecting efficiency in wheat production to identify the critical investments and outline suitable policy directions. Numerous studies in India have estimated the technical efficiency and factors affecting efficiency in agricultural production (Shanmugam 2003; Suresh 2013, 2015; Shanmugam and Venkataramani 2006; Bhende and Kalirajan 2007) and also for wheat crop at farm level as well as regional level (Kaur et al. 2010; Singh 2007; Ahmad et al. 2018; Ramadas et al. 2019b). These studies highlight that technical efficiency is driven by the various socio-economic, agronomic and also climatic factors in the region. Shanmugam and Venkataramani (2006) introduced health

Table 17.7 Descriptive statistics of variables considered for the analysis

Variable	Obs.	Mean	Std.Dev.	Min	Max
Wheat production efficiency (percentage)	180	0.8537	0.1741	0.331	1
Rainfall (mm)	180	949.1	416.0	92.4	1941.4
Avg. size of landholding (ha)	180	1.6	1.0	0.39	4.03
Fertilizer consumption (kg/ha)	180	117.6	58.2	28.6	250.6
Agricultural worker (No./ ha NSA)	180	2.3	1.4	0.84	6.6
Cropping intensity (percentage)	180	149.8	26.1	107.7	191.2
Irrigated area under wheat (percentage)	180	88.9	68.3	18.5	709.8
Tractor density (tractor/000 ha NSA)	180	3.3	1.91	0.34	8.98

Table 17.8 Estimates of tobit regression model of wheat production efficiency

Technical efficiency in wheat production	Coefficient.	SE
Constant	0.223[a]	0.091
Net irrigated wheat area (%)	0.0001	0.000
Tractor density (No./000 ha of NSA)	0.0095	0.007
Rainfall (mm)	0.000	0.000
Avg. size of holding (ha)	0.047*	0.016
Fertilizer consumption (kg/ha)	−0.001*	0.000
No. of Agricultural workers/ha	−0.017	0.010
Cropping intensity (%)	0.004*	0.000
Note: [a]indicate 5 percent level of significance		

status of the farmer is also one of the determinants of efficiency along with other factors.

The factors included in the study are average size of holding, agricultural workers per net sown area, rainfall, fertilizer consumption, cropping intensity, irrigated area under wheat and tractor density. After estimating the state level efficiency score in wheat production, they are regressed on the selected explanatory variables. As the technical efficiency scores are censored between 0 to 1, tobit regression is used (Suresh 2015). Descriptive statistics for the variables selected for analysis is depicted in Table 17.7.

The estimates of the regression highlighted that average size of land holding, fertilizer consumption and cropping intensity significantly affects the technical efficiency of wheat production (Table 17.8). With every one-unit increase in land-holding and cropping intensity, there is 0.047 and 0.004-unit increase in wheat technical efficiency on an average, respectively. However, with every one-unit increase in fertilizer consumption (kg/ha), there is a decrease of 0.001 unit in wheat production efficiency.

17.6 Strategies to Enhance Efficiency in Wheat Production

The rise in productivity in non-traditional wheat growing regions on one side and increasing resource use intensity in traditional regions on other side offer scope for raising both production and productivity more efficiently. Having observed yield in certain states have attained its plateau and opportunities for increasing further land for cultivation are limited, production enhancing strategies shall be shifted towards the states with increasing yield trends despite of their meagre contribution. For instance, yield has increased considerably in Madhya Pradesh, Himachal Pradesh and Bihar during the past decade. While Madhya Pradesh contributes about 15% of total wheat production, Himachal Pradesh contributes less than 1%, and Bihar contributes about 6% of production. States like Uttarakhand and Jharkhand as well have registered notable increase in yield, whose contribution stands by less than 1%. Despite of their limited contribution, these states shall be focused to raise further yield improvements by identifying appropriate factors.

Yield response to fertilizers appears relatively higher in Madhya Pradesh, Himachal Pradesh, Jharkhand and Uttarakhand, whereas it responds less in West Bengal, Punjab and Haryana. It indicates fertilizer use efficiency is relatively higher in the former set of states than the rest, hence production enhancing strategies shall target these states. Oppositely, the latter set of states show low yield growth despite of intensive fertilizer use, which calls for optimizing the use. Response of yield to seed use appears noticeable in West Bengal, and to some extent in Uttarakhand and Gujarat. Improving quality seed use shall further enhance the yield potential in these states. Rather, higher seed use is observed in Bihar, Jharkhand and Madhya Pradesh, which shall be explored for reducing their use without harming the productivity.

As almost entire area under wheat is irrigated in most of the states, there exists limited potential to increase yield by expanding irrigation. Rather, given the notion that irrigation and fertilizer use are correlated and impact yield jointly, reduction in surplus fertilizer use in the above-mentioned states would implicitly direct water use shall also be brought down without affecting productivity. Leaving apart the physical factors, efficient use of resources lies with decision arising from human capital factors such as farmers' ability to use these resources more efficiently. Efficiency indices are relatively low in Bihar, Rajasthan and Uttar Pradesh despite of their contribution. Similar is the case in Jharkhand and Chhattisgarh. Training farmers on appropriate use of inputs in these states and building their capacity to access new technologies would further enhance their efficiency, whose implications on yield shall be substantial. Rising labor cost on the other hand signify the need for adopting mechanization practices. Dependence on labor stands substantially high in states like West Bengal, Rajasthan, Gujarat, Uttar Pradesh and Bihar, where attention shall be given on mechanizing cultivation practices more intensively by facilitating institutional arrangements like custom hiring centres and expanding institutional credit for ownership of low-cost farm implements.

17.7 Conclusions and Way Forward

Improvement in technical efficiency represents one of the pivotal strategies for achieving sustainable food production and livelihood security of the nation. Although, performance of states in wheat production is satisfactory but still there is a scope to increase efficiency in wheat production. In recent period total factor productivity growth of technologically advanced regions is steadily declining which is mainly due to waning of technical change. However, increasing in TFP growth was also observed in states like Jharkhand, Madhya Pradesh and Bihar mainly due to significant improvement in technical efficiency in wheat production. The technical efficiency analysis shows that traditional wheat producing states are operating close to their production frontiers and have very limited scope for output growth. The states like Uttar Pradesh, Bihar, Chhattisgarh have still scope increase in efficiency in wheat production. Further, increase in cropping intensity has positive effect on technical efficiency of wheat production. It is evident that large farm size has advantage of scale economies, therefore reduction in fragmentation of land size is also another option to augment both economic and technical efficiency. Investment instillation is required in R&D to develop improved varieties which can withstand the negative consequences of climate change. Further, policy focus must be directed towards sustainable intensification of crop production to produce more with same or fewer resources.

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Frontier Mechanization Technologies for Wheat Based Cropping Systems

18

Neeraj Kumar, R. S. Chhokar, S. C. Tripathi, S. C. Gill, and Manoj Kumar

18.1 Introduction

Energy consumption has been a key factor for development of every nation. The availability of specific energy (per capita or per unit area) plays a major role in the growth of every sector. In agriculture sector, human, animal, tractors and motors have been major sources of energy for executing the different field operations. In 1960–61, farm power availability was 0.28 kW ha^{-1} which increased to 2.02 kW ha^{-1} in 2013–14, promoting the food grains productivity from 0.64 to 2.11 t ha^{-1} as presented in Fig. 18.1. In the last few decades, energy use pattern in agriculture has been changed drastically, shifting major source of power from draft animals to tractors and power tillers as shown in Fig. 18.2. Animate power, which was 92.5% during 1960–61, is estimated to be reduced to 4.1% by 2033–34, while mechanical power will rise from 5.6% to 82% in this time span (NITI Aayog Report 2018). This transformation has been a driving force to move from traditional farming towards mechanized farming. Mechanization has played a vital role in enhancing the crop productivity and making India self-reliant to meet the food grains demand of burgeoning population. Moreover, drudgery, energy use and time required for completion of various field operations have been reduced substantially with mechanized farming system, thereby allowing to increase the cropping intensity. The mechanization level, which was below 5% in 1960, has been increased to nearly 40% with the usage of tractor/power tillers. This transformation can also be understood by the sales of tractors and power tillers over the years as presented in Fig. 18.3. India is the largest hub for tractor industry, which witnessed 21% growth

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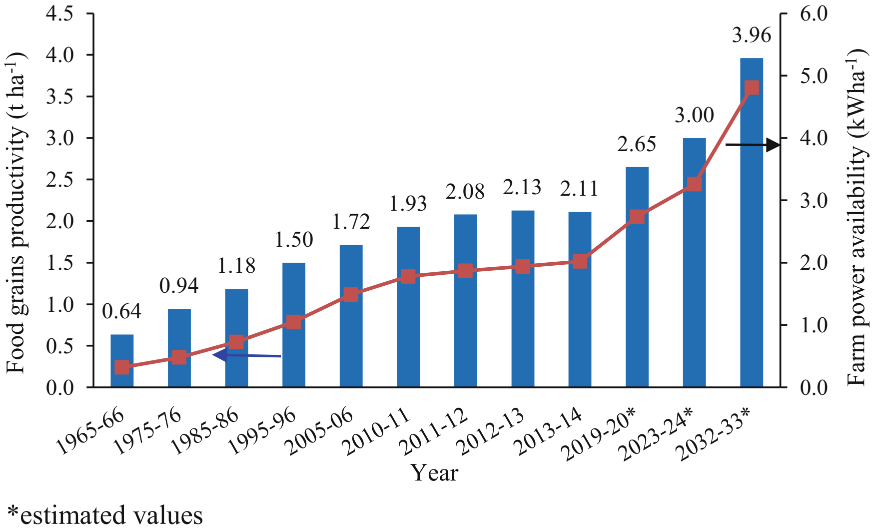

Fig. 18.1 Year wise food grains productivity and farm power availability (Data Source: Singh (2015a, b), GoI (2015), NITI Aayog Report (2018))

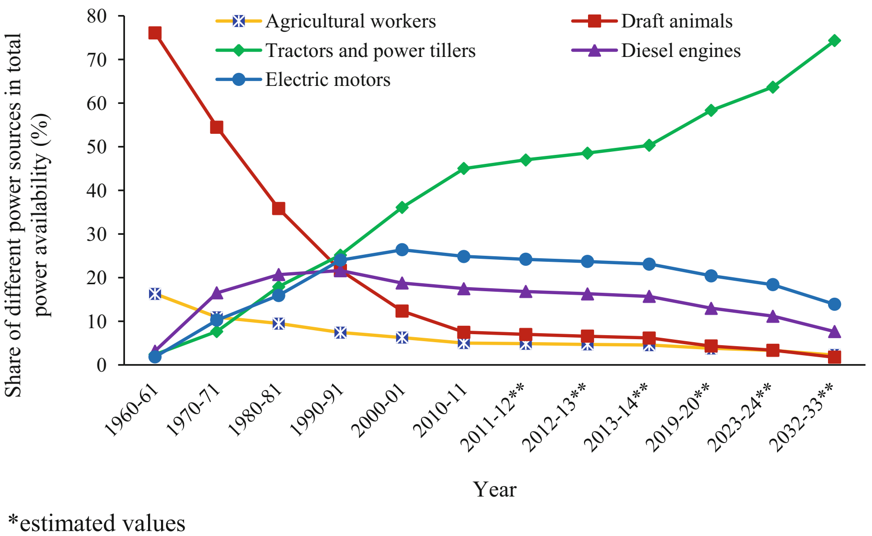

Fig. 18.2 Trend of share of different power sources in total power availability on Indian farms (Data Source: Singh et al. (2014), Singh et al. (2015), Singh (2015a, b), NITI Aayog Report (2018))

in financial year 2019 as a result of rising mechanization level and surge in tractor export. In farm equipment category, tractor captures 81.4% share followed by rotavator (3.7%), thresher (2.7%) and power tiller (1.4%) (FICCI Report 2019).

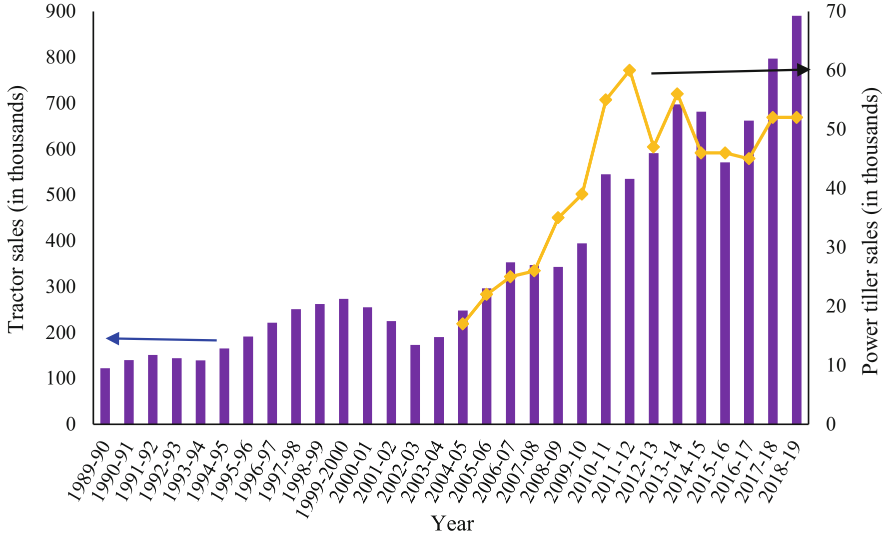

Fig. 18.3 Tractor and power tiller sales over the years [Data Source: Sarkar (2013), GoI (2019)]

Despite these favourable conditions, overall mechanization in India is far below than the developed countries mainly due to small land holdings, different agro-climatic zones, poor economic conditions of farmers, diversity in availability and accessibility of resources across the states, etc. Mechanization in soil tillage and seed bed preparation operation stands close to 40%, while in seeding and planting operations, it counts nearly 29%. In plant protection operations also, mechanization level is low, which is close to 34% (NABARD Paper 2018). Two major crops of food grains namely rice and wheat are being cultivated comparatively in more mechanized way having 60–70% mechanization level in harvesting and threshing operations as compared to other crops having less than 5% mechanization level for these operations (NABARD Paper 2018).

In India, majority of farmers belongs to small and medium land holdings, who either hire the tractors for soil preparation and threshing operations or purchase medium category tractor (31–40 hp) to execute different agricultural operations. In India, about 83% share of tractor market belongs to 30–50 hp tractors (Singh et al. 2011; FICCI Report 2019). However, in recent time, tractor sales data reveals growing interest of farmers in 41–50 hp tractors, which can effectively operate high power requiring implements such as rotavator, laser land leveler, thresher, etc. (NITI Aayog Report 2018; Tiwari et al. 2019). In addition to energy use pattern, changes in farm implements to execute different field operations are also taking place in consideration of timely sowing of crops with minimal input cost, uniformity and effectiveness in spraying operation and effective harvesting and threshing of crops with minimal losses. This chapter highlights the frontier mechanization technologies for tillage, seeding, weeding, spraying, harvesting and threshing operations for wheat based cropping systems with their potential benefits and constraints.

18.2 Frontier Mechanization Technologies for Wheat Based Cropping Systems

18.2.1 Emerging Technologies for Land Preparation and Seeding Operations

During green revolution, mechanization played a prominent role to increase the production of food grains. Farmers have been using conventional tillage practices, thinking necessity of more intense tillage for more crop production. It covers ploughing, disking, cultivating and planking of soil for seedbed preparation followed by seeding and intercultural operations. Tillage has been associated with improved soil macro porosity, soil aeration, proper seed-soil contact, reduced weed infestation, distribution of weed seed bank in various soil layers and better germination and crop yield. However, many researchers expressed their concerns on soil structure destruction, soil quality deterioration and subsurface compaction with intensive tillage practices for a longer time (Abrol and Sharma 2012; Graves et al. 2015; Shah et al. 2017). Therefore, resource conserving implements are being promoted for tillage and seeding operations to reduce the harmful effects of agricultural machinery on soil structure and to minimize the input cost, thereby more profit to farmers.

18.2.1.1 Rotary Tiller/Rotavator and Roto Seed Drill

Rotavator has emerged as popular choice of farmers for seed bed preparation as it tills the soil very finely and also allow mixing of fertilizer/manure with soil. It is an active type tillage implement, which requires lesser draft as compared to passive implement of similar size. However, total energy requirement of machine is higher due to major portion of power taking part in rotary action. Moreover, it is not suitable for sandy soils. It is always desirable to have more crop productivity with lesser input cost in which reduced field operations play an important role. Roto seed drill is one such implement which does the job of seed bed preparation by incorporating the crop residue with soil and seeding simultaneously. The machine is useful for timely sowing of wheat crop in rice harvested field and it saves fuel and time over conventional practice, thereby reducing the cost of cultivation (Sharma et al. 2008; Dixit et al. 2014). However, this machine works effectively in loose residue free field, leaving only anchored residue or with very small amount of loose residue on the soil surface. The need of partial removal of loose residue from rice field before wheat seeding remains as main constraint of this technology for effective in-situ rice residue management (Singh 2015a, b). Furthermore, residue incorporation into soil proposes other challenges of temporary immobilization of nitrogen and higher energy consumption than crop residue retained on soil surface as mulch (Bird 2001; Jat et al. 2010).

18.2.1.2 Strip-Till Drill

Strip-till drill is considered as an intermediate choice between conventional and zero tillage practices. Strip-till drill prepares the soil in narrow strips with the help of rotor blades followed by seeding in the tilled strips. The tilled narrow strips simulates the seed-soil contact to conventional tillage practice, while undisturbed area with crop residue acts similar to no-tillage practice. The use of this machine enables the farmers for early seeding of wheat crop in rice harvested field with similar or higher yield than conventional practice (Shukla et al. 2001; Chaudhary and Singh 2002; Shukla et al. 2008; Hossain et al. 2012). Moreover, farmers reported 30–60% saving in fuel and time and reduced infestation of *phaliris minor* with strip-till drill as compared to traditional sowing (Shukla et al. 2008; Mahal et al. 2009; Hossain et al. 2012). The application of machine is also extended to other crops such as maize, mung, etc. (Reddy 2010). The use of C-type blades in machine reduces the soil handled volume and energy requirement as compared to Roto seed drill and conventional tillage. The machine works effectively under residue free or with anchored residue conditions. However, in combine harvested rice field, farmers need to remove the loose residue or manage it with other suitable machines such as baler, straw chopper, etc., before seeding operation to avoid the residue clogging (Shukla et al. 2001).

18.2.1.3 Laser Land Leveler

Unevenness of the soil surface has the prime effect on irrigation amount, seed germination, plant stand and yield of crops through nutrient water interaction and soil moisture distribution pattern. Laser land leveler is a modern implement, which consist of scrapper, hydraulic system, transmitter, receiver and control box as main components and precisely levels the land. It improves uniformity of water application, water productivity, nutrient-water interactions and crop yield (10–20%) while reducing the irrigation water requirement (20–30%) and abiotic stress intensity (Jat et al. 2006; Kaur et al. 2012). Despite these known benefits of laser land leveler, many Indian farmers still use conventional techniques of land leveling, which are labour-intensive, imprecise and incapable to achieve the smoothness on soil surface. Laser land leveling technique is widely known for reaching higher level of precision in land leveling. Despite its many benefits, high capital investment, high power requirement, less efficient operation in small sized farms and need of trained driver and skilled person are major constraints in the large scale adoption of laser land leveler (Jat et al. 2006).

18.2.1.4 Pneumatic Multi-Crop Planter

Pneumatic multi-crop planter is widely used for planting of vegetables and other crops, where precise plant to plant spacing is to be maintained. Pneumatic multi-crop planter has been used for planting of maize, peas, soybean, pigeon pea, green gram and other crops in wheat based cropping systems (Maheshwari and Varma 2007; Nejadi and Raoufat 2013; Kumar et al. 2013; Khambalkar et al. 2014; Cay et al. 2018; He et al. 2019). Maheshwari and Varma (2007) found improvement in seeding uniformity and plant population, along with reduction in seed rate and labour requirement in pea seeding with pneumatic planter over seed drill. Kumar et al. (2013) reported the lower values of miss index (1.5%) and multiple index (3.5%) along with higher field efficiency of 88% for pegionpea crop sown with pneumatic planter. Nejadi and Raoufat (2013) also reported 31% and 30% reduction in miss index and precision indices, respectively, when maize planting was done with pneumatic planter having row cleaner. The quality of feed index was found to be 72%, which increased up to 11% with row cleaner attachment over control condition. He et al. (2019) found seeding accuracy of 96.6–99.1% in corn planting with pneumatic planter having variable rate seeding control system. The application of pneumatic multi-crop planter to various crops in wheat based cropping systems could be beneficial for optimal plant population and higher yield along with lesser input cost.

18.2.1.5 Rotary Disc Drill

Rotary disc drill is an active type implement for direct seeding of crops under rice residue and sugarcane ratoon with full trash. Soil razor disc blades of machine cut the crop residue effectively even in the early morning and late evening time when residue is comparatively wet (Sharma et al. 2008; Chhokar et al. 2018; Chaudhary et al. 2019). Moreover, with usage of machine, disc blades become sharper, which allows use of machine for longer time without re-sharpening or replacement of blades. Rotary disc drill works effectively for direct seeding of wheat, rice, soybean, pea, barley, gram, soybean, and pigeonpea under crop residue. The machine works satisfactorily for direct seeding of wheat in combine harvested fields (with anchored and loose residue), provided that residue is uniformly distributed in the field (Sharma et al. 2007; Singh et al. 2008a; Jat et al. 2011). The capability of machine in direct seeding of crops under sugarcane trash makes it advantageous over existing machines and suitable for rice-wheat and sugarcane-wheat cropping systems, which covers major area in north-western plain zone (Sharma et al. 2008; Chhokar et al. 2018; Chaudhary et al. 2019). The machine can be used for seeding in diverse residue conditions (anchored, loose and incorporated residue) with minimum soil disturbance (Sharma 2007; Gupta et al. 2009). Presently this machine is available at ICAR–Institute of Wheat and Barley Research, Karnal. It needs to be manufactured commercially for its wide outreach to farmers to discontinue the residue burning from north-western plain zone.

18.2.1.6 Turbo Happy Seeder

Happy Seeder is a popular seeding machine, which was developed by Sidhu et al. (2007) for timely sowing of wheat crop after rice harvest without burning the crop residue. It is an active type implement, consisting of flails mounted on rotor followed by seeding attachment. The latest version of Happy Seeder known as Turbo Happy Seeder (THS) uses inverted gamma type serrated flails, which improved residue cutting efficiency along with lesser energy consumption as compared to previous versions with plain inverted gamma, and J type flails (Sidhu et al. 2015). The machine has been predominantly adopted in the belt of Indo-Gangetic Plains (IGP), where rice-wheat cropping system is extensively followed. Sidhu et al.

(2015) reported 50–60% lesser operational cost along with lower canopy temperature, reduced evaporation losses and lesser irrigation requirement in wheat crop sown with THS over conventional practice. Despite multiple benefits, the adoption of THS on large scale is slow. A few researchers pointed out the inability of machine to work in moist residue, high power requirement, small operational window and unsuitability in direct seeding of wheat crop under sugarcane trash as major constraints in the large scale adoption of THS in sugarcane-wheat growing regions (Sharma et al. 2008; Chhokar et al. 2018).

18.2.1.7 Super Seeder

Super Seeder is another popular soil preparation-cum-seeding machine, which is similar to roto till drill except types of blade used in the machine. However, it has additional attachment of roller, which slightly compacts and levels the soil after the seeding operation. It is an active type implement, which consists of rotavator structure with LJF blades followed by seeding attachment and roller units. Super Seeder performs the bed preparation and seeding operations simultaneously. Moreover, it can be used in residue covered field, thereby incorporates the crop residue into soil followed by seeding operation and compaction of soil. The design of LJF blades provides gentle curve in lateral as well as in vertical direction from cornerite of bending point. It provides the advantage of gradual increase in bite width rather than constant bite width as in L-type blades after striking of blades on soil surface. This design structure of blades reduces the clogging of blades with crop residue and effectively mix it with the soil. However, high power requirement of machine ($\geq$60 hp) over other residue handling machines like RDD and Happy Seeder makes it disadvantageous in terms of capital investment on prime mover and fuel economy especially for farmers belonging to small and medium land holdings.

18.2.1.8 Combined Offset Disc Harrow

Combined offset disc harrow is combination tillage implement having an active i.e. powered gang at front and a passive gang at rear of machine. It provides better soil pulverization, stubble cutting, and crop residue burial efficiency in seed bed preparation with reduced passes and lesser draft as compared to traditional or passive offset disc harrow (Upadhyay and Raheman 2018, 2020a, 2020b). However, total energy consumption of machine is higher over passive offset disc harrow as it utilizes major fraction of energy in rotary action (Upadhyay and Raheman 2020b). It is to be noted that additional energy demand of machine can be minimized by selecting the optimal values of gang angle and velocity ratio. Presently, this machine is not commercial available in the market. Further modifications such as attaching seeding unit with this machine and its commercial production and availability in market might be helpful for the farmers to reduce the energy expenditure in seed bed preparation and seeding operations along with better management of crop residue.

18.2.1.9 Plastic Mulch Laying Machine

Plastic mulch laying machine is a modern implement to conserve the moisture and to improve the water productivity of maize and other vegetable crops in wheat based cropping systems. This machine makes the adjustable raised bed and lay the plastic mulch film on which adjustable marking can be made. It also has the provision of fertilizer drilling. It has been reported that plastic and other biodegradable material based mulching reduces evaporation loss and improves crop water productivity (Liu et al. 2009; Yi et al. 2010; Li et al. 2013; Xu et al. 2015; Ren et al. 2017; Deng et al. 2019; Zhang et al. 2020). However, complete removal of plastic mulch after harvesting of crop could be a challenge, causing soil and environmental pollution. Therefore, black biodegradable film should be promoted for use in mulch laying machine, which can perform similar to plastic film mulching in improving the water productivity of crops (Deng et al. 2019). Moreover, these machines could be modified to have planting mechanism for maize and other crops, which can perform mulch laying and planting operations simultaneously, thereby reducing the input cost and time.

18.2.2 Emerging Technologies for Fertilizer Placement

The placement of required amount of fertilizer, its form and application timing play crucial role in nutrients use efficiency and crop yield. In the last few decades, new technologies have been adopted for fertilizer application, replacing the traditional broadcasting practice. In recent time, technological advancement in fertilizer application extended beyond simultaneous seed cum fertilizer drilling practice. The emerging technologies for fertilizer application are discussed in the following sections:

18.2.2.1 Variable Rate Technology

Variable rate technology (VRT) refers to application of different quantity of inputs (fertilizer, seeds and chemicals) in different segments of the field. It is categorized into sensors-based variable rate spraying and map-based variable rate spraying. In sensors-based variable rate application, specific properties of soil, crop or environmental conditions are measured within the field, which are then processed by computer (Dusadeerungsikul et al. 2020). The calibration of measured properties with input rates allow variable rate controller to apply the required amount of inputs. In this technique, decision on input rates is taken in real time during the field operation. In map-based variable rate application, location-specific prescription map is prepared, which specifies the amount of inputs to be applied at different locations of the field (Dusadeerungsikul et al. 2020). These inputs amount are determined by several soil and crop properties. In this method, input rate is changed by the synchronization of prescription map with actual location of the variable rate applicator as determined by global positioning system (GPS) (Dusadeerungsikul et al. 2020). In map-based variable rate technology, decision on input rates is taken before performing the field operation. VRT has the capability to enhance the productivity and profitability while conserving and keeping our natural resources safe (Fulton et al. 2001). It maximize the resource use efficiency and profitability by supplying the inputs to required place at an optimum dose (Fabiani et al. 2020).

Map- and sensors-based variable rate granular fertilizer application control systems have been developed and tested under laboratory and field conditions in rice and maize crops (Kim et al. 2006; Zhang et al. 2007; Forouzanmehr and Loghavi 2012; Fuadi et al. 2019). The variable rate fertilizer applicator responds to target values with a good accuracy and low application rate error, suggesting its suitability for row crop planters. Moreover, it improves the crop yield along with saving in fertilizer amount, thereby lowering the input cost and improving overall profitability (Mikio et al. 2001; Zhang et al. 2007; Morimoto et al. 2017). Ehlert et al. (2004) reported 10–12% saving in fertilizer amount when site-specific fertilization was done using pendulum-meter in wheat crop. The applicability of VRT is not limited to fertilizers application but also extends to leveling-index based variable rate seeding for more uniform crop establishment over conventional practice (Bakar et al. 2019). Undoubtedly, VRT increases the input use efficiency along with many environmental benefits; however, it is competitive advantageous only under heterogeneous large fields (Thrikawala et al. 1999). The constant application rate of inputs is more profitable under small or homogeneous fields.

18.2.2.2 Deep Fertilizer/Nitrogen Applicator

The deep placement of nitrogen is one of the viable measures to enhance the nitrogen use efficiency especially in rainfed lowland rice, where single dose of entire nitrogen amount is applied during the favorable water regime (Mohanty et al. 1998). This practice is adopted for the soils having percolation rate within 5 cm day^{-1} to avoid the high leaching losses of applied fertilizers and in dryland areas to meet the favorable soil moisture condition (Katyal et al. 1985; Li et al. 2009). The direct rice seeder machine synchronous with deep placement of fertilizer has been used for simultaneous seeding and placement of nitrogen in the form of commercial compound fertilizer ammonia bicarbonate (Pan et al. 2017). Deep placement of nitrogen improved rice grain yield (4.7–8.0%), N recovery efficiency (21.5–50.8%) and N agronomy efficiency (19.5–50.4%) as compared to surface broadcasting method (Pan et al. 2017). In other experiment, grain yield of spring wheat increased by 11% while fertilizer induced N_2O emissions reduced significantly with deep N fertilizer placement (at 20 cm) compared to a shallow placement (7 cm) (Rychel et al. 2020). Deep placement of nitrogen fertilizer also improves the root biomass, which can enhance the soil organic matter and overall soil fertility along with higher net returns to the farmers (IFDC Report 2017; Hossen et al. 2019). Solid or liquid manure placed with deep placement technology provides deep rooting, improved nutrient uptake and better yield than broadcast application (Nkebiwe et al. 2016). However, deep placement of N fertilizer in wheat is more advantageous in fertile soil having sufficient nitrogen to meet the wheat seedlings demand (Wang et al. 1995). Despite multiple benefits with deep placement technology, its adoption among farmers is slow due to lack of simple and effective deep fertilizer applicators.

18.2.3 Modern Technologies for Weed Control

Timely and proper weed control play a vital role in productivity and profitability of any cropping system. Mechanical weed control strategies are more suited to crops such as maize, sugarcane, cotton, etc., where wide spacing of row to row and plant to plant is to be maintained. The crops with continuous plants i.e. where plant to plant spacing is not maintained such as rice, wheat, gram, etc., require chemical approach for controlling the weeds in an effective and economical way. A few modern spray technologies and implements for controlling the weeds are discussed below.

18.2.3.1 Electrostatic Sprayers

The effectiveness and cost in controlling the weeds by chemical approach depends on its characteristics as well as spraying technology. The conventional spraying system suffers from certain constraints like poor deposition efficiency, poor distribution and low penetration into dense plant canopy, which reduces system efficacy along with higher input cost (Subhagan et al. 2016). The modern spraying technology like electrostatic sprayers are reported to improve the deposition efficiency and distribution of droplets, thereby enhancing the uniformity of application (Esehaghbeygi et al. 2010; Patel et al. 2017). Such sprayers induce the charge in liquid droplets to improve the deposition of liquid droplets on the target surface. In electrostatic sprayer, chemical deposition on plant leaves could be as high as 2–3 times to that of conventional sprayer (Mamidi et al. 2013). However, such performance is strongly dependent on operational parameters such as voltage, application pressure, spraying height, flow rate, travel speed, electrode material and nozzle orientation (Appah et al. 2019). Parham (1982) reported similar level of control of shepherd's purse weed in spring and winter wheat when herbicide was applied in ultra-low volume (<4 l ha^{-1}) with electrostatic sprayer over conventional sprayer. Esehaghbeygi et al. (2010) found improved deposition of droplets and herbicide efficacy in controlling the weeds of wheat crop using electrostatic sprayer. The application of electrostatic spraying also reduces chemical usage (by 30%), fuel consumption and operational energy in addition to reduced pollution of air and soil (Tanasescu et al. 1999).

18.2.3.2 Variable Rate Spraying

Variable rate spraying permits the operator to apply adjusted volume rate of chemical to the target based on prescription map, sensors or machine-vision system in a cost-effective and environment friendly way. In variable rate spraying, flow rate is adjusted according to weed infestation or density, soil properties and plant canopy. Map- and sensors-based variable spraying are discussed below.

Map-based Variable Rate Spraying

Map-based variable spraying has been adopted to improve the herbicide efficacy and to reduce the chemical usage in controlling the weeds of various crops such as wheat, maize, barley, etc. (Gerhards et al. 2002). Brown et al. (1990) reported 25% reduction in herbicide use in manually controlled spray system based on geographic information system (GIS) weed map. However, operator finds the difficulty in simultaneous work of locating the weeds in the field and accordingly controlling the flow rate of sprayer. It was recommended that automatic spray-control system with a weed sensor can address such challenges and to further reduce herbicide use in the crops. The modern map-based variable spray technology uses field coordinates from a GPS receiver and prescription map to change the application rate as applicator moves through the field. For a particular location of the sprayer, a system sends the signal to control system to change the application rate based on various strategies using the data of weed map, soil type, soil color, texture and remotely sensed images. Different types of control systems such as flow based control, chemical injection based control and modulated spraying nozzle control systems have been used in map-based variable spraying (Grisso et al. 2011), which are discussed below.

Flow Based Control System

Flow based control system is the simplest control system, which regulates the flow rate of tank mix to target application rate by integrated working of groundspeed sensor, servo valve and electronic controller. However, this control system regulates the liquid flow by allowing variable pressure at spray nozzles, which can cause major changes in size and drifting of droplets.

Chemical Direct Injection Based Control System

The system of chemical direct injection controls the output rate of chemical rather than delivery rate of tank mix with the help of controller and chemical pump while allowing constant rate of carrier (water). This system ruled out the issue of leftover tank mix and reduces the chemical exposure time. Moreover, optimum desirable size and distribution of spray droplets can be obtained by adjusting the flow rate of carrier. However, long transport delay between source point and delivery at nozzles is the major disadvantage of this system. This problem is eliminated in chemical direct injection with carrier control system in which one control loop regulates the injection pump while other controls the servo valve to deliver the matching flow of carrier. However, this system is more complex and expensive. The major disadvantage of this system is that with change in flow rate, varying amount of liquid through nozzles causes to change the droplet size and spray characteristics.

Modulated Spraying Nozzle Control System

In this control system, timing and duration of discharge from nozzles is regulated with the help of in-line solenoid valves, microprocessor and application controller (Fig. 18.4). This system works for wide range of flow rates with more consistent spray characteristics. This system offers the advantage of changing flow rate as per requirement without any effect on droplet size and distribution pattern. Moreover, droplet-size distribution can be varied to minimize the drift near sensitive areas without changing the application rate.

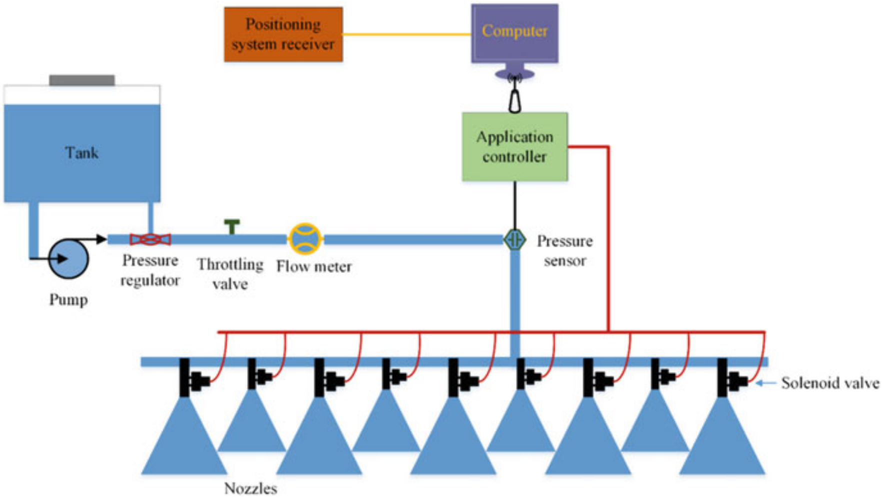

Fig. 18.4 Modulated spraying nozzle control system

Sensors Based Variable Rate Spraying

Sensors based varying rate spraying systems do not require map or positioning system. In such systems, specific sensors (optical or infrared sensors) or machine vision system mounted ahead of the nozzles is used for measuring the crop and soil characteristics. Sensors based variable spraying system can reduce the chemical application amounts in variable weed infested fields. Felton et al. (1991) reported that optical sensors based spraying system can be used for detecting the plants on the soil background, thereby enabling it for postemergence herbicide application in the cereal crops such as wheat. Chancellor and Goronea (1994) reported 40% increase in input use efficiency of herbicide application with spatial variability based spraying operation in wheat crop. Chaisattapagon (1995) used machine vision based on color, shape and texture analysis approaches for detection of weeds in wheat crop. The transformation of wheat leaf images into Fourier spectrum showed one-way texture pattern, which differed from multidirectional texture patterns of weeds such as wild buckwheat, palmer amaranth and kochia. It was concluded that texture directionality approach can be applied for detection of weeds in crops.

18.2.3.3 Sensors-based Mechanical Weed Control

The evolution of new weeds and increasing resistance against herbicide has forced researchers to rethink about integrated weed control strategies rather than relying solely on chemicals. Moreover, concerns have been expressed on harmful effect of chemicals on product quality, which encouraged the farmers to adopt organic farming. Either, it is conventional or organic farming, integrated effective weed control strategy is a key to improve the productivity and profitability of crops. Camera assisted mechanical weeders and robotic weeders have been used for weed control in crops such as maize, soybean and sugar beet, which have been reported to improve the weeding efficiency over manually guided mechanical weeders (Rueda-Ayala et al. 2010; Kunz et al. 2018; Fennimore and Cutulle 2019; Machleb et al. 2020). However, in mechanical weeding, some weeds are left near the plant area and weed control efficacy of weeders is generally lower than herbicide application method. Rueda-Ayala et al. (2015) used ultrasonic sensors based automatic harrowing system for controlling the weeds in maize crop. The detection of weeds and their density was done using ultrasonic sensors which allowed to change the tine angle automatically for a variable intensity of harrowing. The mean weed control was found to be 51% without any significant crop damage. Nevertheless to say that sensors-based mechanic weed control strategies could be useful for controlling the weeds in row crops and vegetables. Fennimore et al. (2016) reported that downward fashion in new herbicide development will continue, while automatic weed removal system continues to progress and emerge as more effective. However, it requires further research on improving crop/weed recognition and physical weed control actuators along with more trainings to students on robotic weed control engineering to extend the sensors-based mechanical weed control strategies to cereals crops (Fennimore and Cutulle 2019).

18.2.4 Emerging Technologies for Harvesting and Threshing Operations

18.2.4.1 Self-Propelled/Power Tiller Operated Vertical Conveyor Reaper

Vertical conveyor reaper (VCR) proved to be a cutting edge technology for harvesting the rice and wheat crops amid rising labour scarcity problem. It is more feasible and economical choice for farmers belonging to small and medium land holdings to harvest the rice and wheat crops. This machine can either be self-propelled or power tiller operated with or without binding mechanism. VCR performs the task of harvesting the crops in lesser time (85%) along with reduced drudgery, labour (81%) and harvesting cost (30–40%) over manual method (Singh et al. 2008b; Murumkar et al. 2014; Debnath and Chauhan 2020). Also, lower harvesting losses have been observed with VCR as compared to manual harvesting (Patel et al. 2018; Debnath and Chauhan 2020). However, farmers belonging to medium and large land holdings having their own combine harvesters or accessibility to custom hiring service of such machines, can go simultaneous harvesting and threshing of crops as total losses in combine harvesting are lower than individual operation i.e. harvesting with VCR followed by threshing operation (Pawar et al. 2008).

18.2.4.2 Pedal/Solar Operated Paddy Thresher

Threshing is a very laborious and drudgery operation. Pedal or solar powered paddy thresher with wire loop threshing mechanism proved to be a major intervention for small and medium scaled farmers of West Bengal, Odisha, Bihar, Sikkim, Assam, Himachal Pradesh and Uttarakhand adopting rice-wheat, rice-toria-wheat, rice-wheat-pulse or other rice involving cropping systems (Agrawal 2008). Pedal operated paddy threshers have grain output capacity of 40–50 kg h^{-1} along with high threshing efficiency (>96%), depending on crop variety, grain to straw ratio, moisture content and operational conditions (Agrawal 2008; Singh et al. 2008c). With power source like internal combustion (IC) engine and photovoltaic cell, the output capacity can be increased to 3–5 times over manual operation. However, solar operated paddy thresher provides the advantage of non-pollution operation over IC engine operated paddy thresher (Sahu and Raheman 2020).

18.2.4.3 Multi-Crop Thresher

Multi-crop thresher allows threshing of various crops like wheat, maize, rice, gram, sorghum, soybean, etc., with a single machine and saves the capital cost. Multi-crop threshers of various sizes have been developed and tested under field condition for threshing of different crops (Singh et al. 2008d; Dogra et al. 2014). Multi-crop threshers perform the operation efficiently (threshing efficiency >97.5%) along with minimal grain breakage (up to 2%) (Idris et al. 2019). Farmers having their own multi-crop threshers or accessibility to custom hiring service allow them for timely completion of operation along with reduced labour, drudgery and threshing cost (Pandey and Stevens 2016; Idris et al. 2019).

18.3 Conclusions

In this chapter, the role of mechanization in improving the productivity and profitability of various crops have been described. In the last few decades, a major shift in farm power sources emerged as a noble indicator for further acceleration of mechanization level in various field operations. In addition to mechanization, input use efficiency of wheat based cropping systems need to be enhanced for better productivity and profitability. The use of resource conserving technologies in tillage, seeding/planting, fertilization, spraying and threshing operations can play prominent role in improving the crop productivity and quality of natural resources base in long-term. Seeding or planting machines, allowing the surface retention/incorporation of residue, should be adopted in wheat based especially rice-wheat cropping system on the large scale for reducing the input cost and managing the crop residue in an environmentally sound manner. The adoption of variable rate technology for need based application of fertilizers and herbicides in wheat based cropping systems can further reduce the input cost and harmful effect of synthetic fertilizers and chemicals on the environment. The use of emerging technologies such as VCR, solar operated paddy thresher and multi-crop thresher in harvesting and threshing operations could be beneficial in reducing the operational cost and losses while improving the mechanization level on small and medium sized fields under wheat based cropping systems. Amid various benefits, adoption of these technologies except few has been very slow on farmers' field. There is a need to strengthen research and development, commercial production of emerging implements and tools, accessibility of service at local levels and field demonstrations and trainings to popularize such frontier mechanization technologies among farmers.

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Innovative Pathways to Increase Resource Conservation and Nutrient Use Efficiency in Rice-Wheat Cropping Systems for Food Security and Decreased Environmental Footprints

19

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19.1 Introduction

The present and coming generations face a range of global challenges: food insecurity, health and nutrition concerns, uneven distribution of wealth and diminishing resources, climate change, environmental degradation (Bhatt et al. 2016a). The challenges above are linked and regulated in one or other way by the intensive, high input current agriculture system. Through eras of ancient and medieval times, communities have been deeply fascinated in improving crop yields by the addition of various mineral or organic ingredients. This character/nature of humankind escalated manifold in the industrial era through the innovation and production of diverse agricultural inputs. One significant milestone was the discovery of the Haber–Bosch process for ammonia synthesis in the early 1900s that enabled the widespread fertilization of croplands relatively at a lower price which resulted in skyrocketed world's population from 1.6 billion to 7 billion during the twentieth century. The rational of feeding 11 billion people by 2050 is challenging under dramatic climate

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change and soil degradation, with average global temperature projected to increase by 4–5 °C (1990–2090). The challenges amplify through various factors such as non-judicious use of inputs, fragmented landholdings, biotic and abiotic stress to attain sustainable production.

The Indo-Gangetic Plain (IGP), breadbasket of South Asia also known as Indus-Ganga and the North Indian River Plain, is a 255 million hectare (630 million acre) fertile plain encompassing most of Northern and Eastern India, the most populous parts of Pakistan, Nepal and virtually all of Bangladesh (Sapkota et al. 2015). With a population of about 800 million, it has been a food bowl for centuries but now severely affected climate change, stagnation in crop production, soil degradation, environmental pollution, conversion of agricultural land into construction colonies. Achieving food security under the regime of climate change will require a holistic system approach, incorporating the principles of resource conservation, efficient and judicious input management with a key consent of sustainable and climate resilient production system. This chapter caters best bet strategies and solutions for efficient and effective resource management in South Asia for rice-wheat cropping system.

19.2 Rice-wheat cropping system (RWCS) in South Asia

Being world's largest production system rice (Oryza sativa L.)–wheat (Triticum aestivum L.) cropping system covers around 24 million hectares in Asia. Rice is traditionally grown in this area by periodic wet tillage followed by seedling transplantation into the puddled soil, whereas wheat is generally grown (in rice residue burnt fields) by broadcasting/drilling of seeds after field operations like disking, tilling, and planking (Bhatt 2015). Seedbed preparation involving operations oxidize the organic matter present in it, disintegrating the macro-aggregates into the micro-aggregates, which affect the soil properties adversely (Das et al. 2014; Roper et al. 2013). Moreover, soil perturbation by traditional tillage causes the soil to act as a source rather than a reservoir of pollutants in the atmosphere, not making it sustainable and environment friendly (Busari et al. 2015). Prior to the mid-1960s, only macronutrients were supplied by the use of commercially available fertilisers; however, as soil health deteriorated, micronutrient shortage began to emerge in the rice-wheat series. Decline within the yield of rice-wheat system was highest once N-fertilizer applied alone at the rate of 120 kg ha^{-1} whereas in 10 years P-fertilizers well-versed crop yield and in 5 years the response from K-fertilizer was enhanced and continuous use of N- fertilizers, intensive rice-wheat cropping sequence, imprudent use of fertilizers, inappropriate fertilizer management and its timing, insufficient application of organic manures, exorbitant use of N-fertilizers, the antagonistic reaction between some plant nutrients had resulted to yield decline in contrasting climate(Bhatt et al. 2016b). IGP of South Asia witnessed green revolution but soon doomed with several adverse consequences on air, soil, water and human leading to stagnation in production system.

19.2.1 Threats Concerning Recession in Productivity of RWCS in Indo-Gangetic Plains (IGP) of India

The long-term viability of traditional rice-wheat cropping systems has been adversely affected by a number of factors. Because of various factors and their compounded effects, some studies recorded stagnant or even lower yields in RWCS. (Dawe 2000; Mishra et al. 2016).

Deteriorating soil health, less soil organic matter (SOM) content, water shortages, nutrient imbalances, labour and energy crises are the key causes of yield stagnation. (Bhattacharyya et al. 2015; Singh et al. 2018a); problematic insect and weed; the emergence of herbicide-resistant weeds (Ladha et al. 2007; Bhatt et al. 2016a; Yadav et al. 2016); poor management of agro-inputs, deteriorated irrigation water quality, and the inappropriate management of crop residues contribute to GHG emissions and pollution (Ladha et al. 2007; Mishra et al. 2014; Srivastava et al. 2016). Indeed, in traditional rice-growing systems, puddling increases soil bulk density, resulting in soil compaction (Farooq and Nawaz 2014; Chaudhari et al. 2015) and affects root development in post-rice crops. Large amounts of water is required in conventional rice production system, 1 kg of rice production require 3000–5000 L (Geethalakshmi et al. 2011). As a result, the potential production of rice in traditional systems is adversely affected due to water scarcity. Difficulty in management of weed because of their transformation to mixture of grassy and broadleaf weeds as a consequence of the introduction of semi-dwarf, high-yielding wheat varieties; herbicide resistance has exacerbated this problem in RWCS. (Yadav and Malik 2005). The pests and diseases in RWCS have increased as a result of the continuous growing of rice and wheat in a row (Bhatt et al. 2016a). In the last few decades, the increased use of combine harvesters in RWCS has resulted in difficulty in management of large quantities of crop residues on the soil surface after harvest. In traditional RWCS, excessive tillage has also resulted in a decrease in SOM. (Bhatt et al. 2016a).

As rice-wheat system is exhaustive in nature and when there is low fertilizer input from external sources, micro and macronutrient deficiencies are becoming more frequent in RWCS (Alam et al. 2006; Kumar et al. 2018a). Land and water productivity of rice-wheat system has also decreased (Timsina and Connor 2001). Despite the fact that resource-conservation technologies were implemented several years ago in RWCS, their implementation has been prolonged. Wheat blast has recently emerged in Bangladesh and India (Chowdhury et al. 2017; Khan, 2017; Singh 2017), and if not managed, it will quickly spread across South Asia, including Pakistan and Nepal.

The transplantation of rice seedlings in RWCS is delayed due to labour shortages during transplanting caused by rapid industrialization and subsequent migration of people from farmlands to cities (Farooq et al. 2011). Heat stress can occur during the reproductive and grain-filling stages of late-transplanted rice, resulting in lower grain yields. Droughts are expected to become more common in the coming years, according to climate models (IPCC 2007). Temperature (>33.78 °C) at anthesis results in panicle sterility and poor anther dehiscence (Jagadish et al. 2007) and temperature (>34.8 °C) during grain formation may result in substantially reduced grain yields (Morita et al. 2002). Spikelet sterility observed by heat stress in rice (Zhang et al., 2018). An increase in the mean temperature above 35 °C hampered flowering and grain formation in rice (Kumar et al. 2015).

19.2.2 Potential of IGP to Hike the Production of RWCS Through Climate-Resilient Agriculture

RWCS are the most important agricultural systems because they are a staple food for the majority of the human population in South Asia. RWCS is currently under extreme stress and is not delivering outputs in accordance with inputs and expectations. Climate change further complexes the scenario in one or other way. Therefore, the intervention of climate-resilient technologies is urgent for improving water productivity in an enormous water use RWCS of South-Asia. Conservation agriculture, nutrient management, and biofortification methods are all viable options for increasing production in a sustainable manner. Some of the potential approaches to mitigate threats in RWCS in South Asia has been enlisted in Table 19.1.

19.2.2.1 Conservation Agriculture (CA)- Concept, Progress and Way Forward

The four core principles of CA are: (1) improving soil health and SOM by minimizing soil disturbance; (2) Use of cover crops and crop residues to enhance SOM; (3) crop diversification in sequences, associations and rotations to enhance system resilience; (4) controlled draft to lessen soil compaction (FAO 2009). Thus, CA avoids straw burning, improves SOC content, enhances input use efficiency and has the potential to reduce greenhouse gas emissions (Bhattacharyya et al. 2012; Mishra et al. 2018). Globally, CA is being practiced on about 157 M ha (FAO 2015). The major CA practicing countries are USA (35.6 M ha), Brazil (31.8 M ha), Argentina (29.2 M ha), Canada (18.3 M ha) and Australia (17.7 M ha). In India, CA adoption is still in the initial phases and expanded to about 1.5 million hectares (Table 19.2).

CA offers a low-cost strategy for resource conservation, soil heath management, GHG mitigation to address the problems and threats of conventional RWCS and non-judicious use of inputs.

19.2.2.2 Potentials of Direct-Seeded Aerobic Rice (DSAR) to Reduce Environmental Footprints

In the absence of standing water, the rice crop is sown directly into unsaturated, well-drained and non-puddled soil in DSAR (Bouman et al. 2005; Mishra et al. 2020).

Rice grown in these systems matures faster than rice grown in traditional puddled transplanted rice (PTR), requires less water (Farooq et al. 2011), and can reduce GHG emissions (Pathak et al. 2014; Kumar et al. 2018c). Figure 19.1 shows comparative features of traditional and that of aerobic system rice. The earlier maturity in DSAR allows timely sowing of the wheat and other crops (Farooq

Table 19.1 Various factors leading to sustainability issues of intensive Rice-Wheat cropping system (RWCS) in South Asia, their causes, impacts and adaptive measures to be taken

Threats to RWCS	Various aspects of issues	Causes of sustainability issues in RWCS	Impacts on various resources	Adoptive measures	References
Ecological aspects	The declining underground water table	Puddled transplanted rice is a massive water consumer. Indiscriminate use causes huge consummation of required green and blue water	Rise in cost for pumping underground water; increase in cost of tube-well infrastructure; and reducing groundwater quality	Un-puddled direct-seeded rice (UPDSR), soil matric potential based irrigation, short-duration cultivars	Geethalakshmi et al. (2011), Soni (2012)
	Groundwater pollution	Excessive fertilizers and insecticides use in RWCS	Grievous diseases in livestock, decreasing grain quality which consequently impacts the health of human beings	Appropriate usage of the fertilizers based on the soil test reports	Bhatt (2013)
	Diverse weed flora	Alteration in establishment process, techniques and weed management practices in dry direct-seeded rice (DSR).	Yield declines	Integrated weed management, region-specific management	Chauhan and Johnson (2010), Singh et al. (2015), Bhatt et al. (2016a), Ladha et al. (2007), Kumar et al. (2018b)
	The outburst of diseases, insects and pests.	The excessive dose of Nitrogenous fertilizers and frequent irrigations monoculture system	Lower water and land productivity yield stagnation	More tolerant crop cultivars	Sehgal et al. (2001), Bhatt et al. (2016a)
Agronomic aspects	Degrading soil structure	Tillage under wet conditions (Puddling)	Sub-surface compaction hinders the root growth by creating aeration stress	Application of organic matter	Saharawat et al. (2010), Kumar et al. (2018c)
	Declining soil health	Structural degradation Intensive tillage results in the large aggregates	The enhanced cost of cultivation as short-term consequences and	Optimum use of organic carbon sources (green	Bhatt et al. (2016a), Choudhary et al. (2018)

(continued)

Table 19.1 (continued)

Threats to RWCS	Various aspects of issues	Causes of sustainability issues in RWCS	Impacts on various resources	Adoptive measures	References
		breakdown. the nutrient balance has been disturbed in the upper vadose zone by Intensive RWCS.	affected soil quality and productivity in the long term.	manure, FYM), legume in rotation, balanced nutrition	
	Residue management	Burning of the rice residues to ensure timely sowing incorporation of rice straw causes the immobilization of nitrogen (being more comprehensive in C: N ratio);Also, higher silica content in rice straw makes it inapplicable in the dairy sector);	Environmental pollution, global warming, killing the beneficial insects, create net negative nutrient balance and also degraded the soil, decreases organic matter levels and ultimately in deterioration of the soil health	Paddy compost Crop residues for energy, ethanol, biogas production, fast pyrolysis "Bio-oil." Slow pyrolysis Biochar	Yadwinder-Singh and Sidhu (2014), Bijay-Singh et al. (2008)
	Least attended intervening period	Ignored one declining water and land productivity of an area	Faster drying of the zero tilled (ZT) mulched plots during intervening periods due to increased soil temperature, lesser available soil moisture, continuity of soil pores, and elevated evaporation losses	Growing summer moong and fodder	Bhatt and Kukkal (2014)
	Labour shortage	Narrow window period and legal binding to transplant paddy	Higher wage rates, lower land and water productivity, lower yields	Mechanical transplanting and direct-seeded aerobic rice	Kamboj et al. (2013), Farooq and Nawaz (2014)

	Multiple nutrient deficiencies	Micro-nutrients deficiencies in the rice-wheat system	Manganese deficiency and selenium toxicity	Integrated nutrient management	Dwivedi et al. (2017), Bhatt (2015), Kumar et al. (2019)
	Declining crop response	Declining land productivity, low N use efficiency (especially in rice where it is only 30–40% of applied N) due to surface runoff, ammonia volatilization, leaching and denitrification	Stagnant yield	Enhancing nutrient use efficiency	Mahajan et al. (2008), Sharma et al. (2019a)
Livelihood issues	High energy requirement	Use of centrifugal pumps for irrigation requires high energy	Diverting electricity from the industrial to the agriculture sector will create more problems like unemployment, electricity shortage	Short duration varieties, upland aerobic rice	Hira (2009)
	Decreased land productivity	Different factors and their compounded effects	Loss in yield	Bed planting, laser land levelling, direct-seeded rice (DSR), direct drilling of wheat seeds in the untilled soils in standing rice stubbles, mechanical transplanting, and implementing some new breed some higher-yielding cultivars out the region, water stress and salt-tolerant, nutrient and water use efficiency (NUE and WUE) disease-resistant varieties.	Dawe (2000)

(continued)

Table 19.1 (continued)

Threats to RWCS	Various aspects of issues	Causes of sustainability issues in RWCS	Impacts on various resources	Adoptive measures	References
	Decreased water productivity	Puddling	Lower yields	Integrated water used strategies	Humphreys et al. (2010), Bhatt (2015)
	Decreased water use efficiency	Puddling	Yield stagnation	Omission of the puddling practices and opt for the direct-seeded rice/ mechanical transplanting of rice	Mishra et al. (2020)
	Poor incomes	Deterioration of the soil structure, formation of the hardpan and declining underground water table, infestation of insect pests, diseases and weeds	decreased land productivity, poor livelihood	Yield enhancement	Bhatt et al. (2016b)
Climate aspects	Environment pollution	Rice stubble management, Smouldering	Smouldering of nutrients and degrading soil physical and biological health reduced air quality, human respiratory ailments, and the death of beneficial soil fauna and microorganisms	Use as mulch material in the upcoming wheat crop to increase crop yields, conservation of soil moisture, and protect the environment.	Gupta et al. (2004), Mishra et al. (2020)
	Global warming	Flaming of farm residues generates ample amount of greenhouse gases and aerosols and other hydrocarbons to the	the direct or indirect effect on the radiation balance regional increase in the levels of aerosols, acid deposition, increase in	Short duration varieties, precision land levelling, direct-seeded rice, tensiometers based irrigation, alternate wetting and drying, mechanical	Jain et al. (2014); Anjali et al. (2019)

		atmosphere affecting the atmospheric composition.	tropospheric ozone and depletion of the ozone layer	transplanting and direct drilling of the wheat seeds in standing rice stubbles (zero tillage using Happy Seeder)	

Table 19.2 Area under global adoption of CA as resource conservation technologies

Countries	Area (M ha)	% of global area	Year
USA	35.60	22.7	2009
Brazil	31.80	20.3	2012
Argentina	29.20	18.6	2013
Australia	17.70	11.3	2014
Canada	18.30	11.7	2013
Russian Federation	4.50	2.9	2011
China	6.67	4.2	2013
Uruguay	1.07	0.7	2013
India	1.50	1.0	2013
Paraguay	3.00	1.9	2013
Kazakhstan	2.00	1.3	2013
(Source: FAO 2015)			

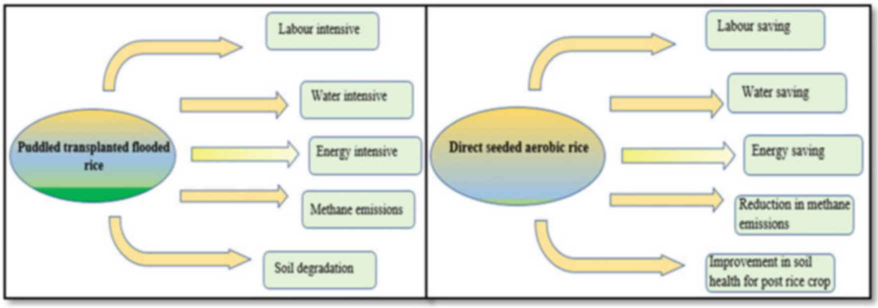

Fig. 19.1 Puddled transplanted rice versus direct-seeded aerobic rice in terms of resource use and effect on soil properties

et al. 2011), thus improving post-rice crop performance and yields (Farooq et al. 2008; Farooq and Nawaz 2014).

19.2.2.3 No-Tillage/Reduced Tillage Wheat for Enhancing Productivity and Profitability

The sowing of crop directly into unploughed fields is known as no-till (Erenstein 2002). In wheat, NT improves input-use performance, maximises crop productivity, boosts farmer profits, and lowers GHG emissions (Aryal et al. 2015; Sapkota et al. 2015). Figure 19.2 shows the conventional tillage wheat versus no-tillage (conservation) wheat in terms of resource use and effect on soil properties. Laser-leveling technology has a lot of potential for saving water and rising efficiency, as well as improving the climate and grain yields (Jat et al. 2014).

19.2.2.4 Pathways and Strategies for Nutrient Management

To increase the efficiency and sustainability of RWCS, various nutrient-management options must be evaluated and integrated (Singh and Sidhu 2014). N, P, and K, three

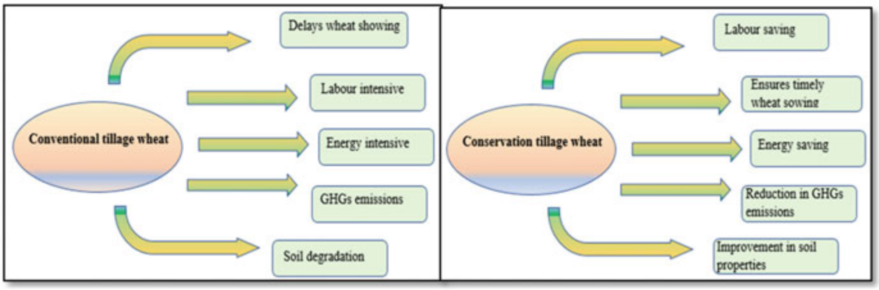

Fig. 19.2 Conventional tillage (CT) wheat versus no-tillage (NT) wheat concerning resource use and effect on soil properties

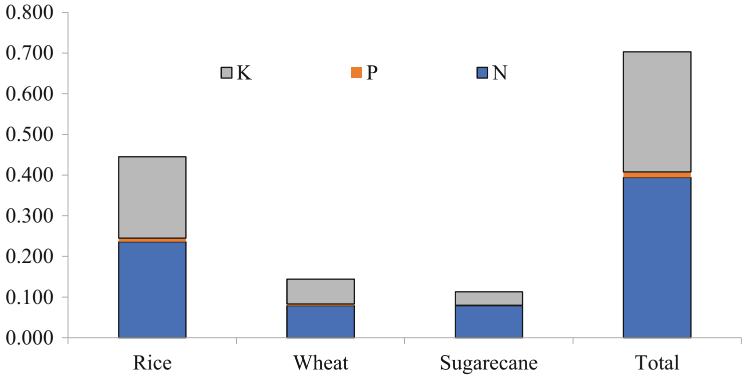

Fig. 19.3 NPK loss from different crop residue burning (Jain et al. 2014)

of the most important crop nutrients, need specified management in RWCS (Dwivedi et al. 2017).

19.2.3 Resource Conservation Technologies in RWCS

19.2.3.1 Crop Residue Management

Globally, principal practice of managing crop residue involves removal, incorporation and burning of residues. Agricultural residues burning may emit significant quantity of air pollutants like CO_2, N_2O, CH_4, which is responsible for global climate change and causes nutrient loss (Fig. 19.3) as well as soil degradation. Nutrient content in rice straw at harvest ranges from 6–8 kg for N, 0.8–1.5 kg for P, nearly 15 kg for K, and 40–70 kg Si per ton of rice straw on the basis of unit dry weight. Whereas, wheat residue contains 4–5 kg N, 0.7–0.9 kg P, and 9–11 kg K per ton (Singh and Sidhu 2014).

Practice of incorporating crop residues into soil system has enormous benefits in RWCS, which includes an improved soil pororsity, hydraulic conductivity infiltration rate and reducing compaction and provides a better soil quality index (Singh et al. 2005; Choudhary et al. 2018).

19.2.3.2 Carbon Trading: A Strategy for Sustainable Production System

In recent years carbon trading industries has been developed to fulfill the purpose of a reduced carbon emissions and to control the deleterious impacts of global warming on environment (den Elzen et al. 2013). As discussed earlier, in IGP resource conserving tecgnologies viz. DSAR and NT wheat are acquiring strength especially in RWCS. Indian farmers are needed to be motivated to take part in carbon trading for mitigating the harmful effects of global warming due to carbon emission (Kumar et al. 2018c; Singh et al. 2018b).

19.2.3.3 Diversification of RWCS with Grain Legumes and Other Crops

Legumes could be added as a subordinate part in RWCS for assuring long term sustainability of the system in terms of productivity as well as environmental and soil health. Reports suggests rice- wheat along with potato and mung bean system in between showed commandable effect on production efficiency and productivity of the system as a whole (Singh et al. 2012). Among legumes, especially mung bean have been seen to have significant effect on system productivity when included in RWCS as well as rice-maize system in north-west IGP of India (Mishra et al. 2018; Choudhury et al. 2018). Therefore, crop diversification have a greater role to play with improved land and water productivity in rice based cropping systems.

Farmers are confused regarding the selection of suitable climate-smart technology (CST) viz., laser land levelling, un-puddled direct-seeded rice (UPDSR), soil matric potential based irrigation, double zero tillage in wheat followed by rice, raised bed planting, short-duration cultivars and correct transplantation time, for enhancing their livelihoods through increasing land and water productivity on one side and mitigating global warming consequences on other (Mishra et al. 2016). Performance of these technologies is both site and situation-specific, and care must be taken in practising them.

19.3 Emerging Environmental Issues and Challenges due to Intensive RWCS

Having an enormous area under cultivation RWCS is considered as the soul of food production in South Asia. Studies revealed the challenge towards sustainability of this system due to mnay underlying factors (Ladha et al. 2009; Yang et al. 2020). Some of the factors considered responsible for its less profitability is its intensiveness in terms of labour, capital, water and energy. Studies over the years also witness the deteriorating soil health as a result of intensive rice-wheat cultivation which has aggravated exhaustion of essential nutrients from soil under cultivation (Choudhury et al. 2014). Not only cultivation practices but also the after-harvest crop residue management is imposing severe threats to the environment in terms of global warming, specifically in a country like India where peasants are not aware of the consequences of residue burning and the alternatives for their management (Parihar et al. 2016; Singh et al. 2018b). To deal with various environmental as well as sustainable issues of RWCS, serious measures need to be taken and gaining knowledge regarding the causes aggravating these conditions from years is the need of the hour. So, taking given this aspect, a straightforward approach to the consequences of intensive RWCS is being discussed in this section.

19.3.1 Deterioration Soil Health in RWCS

From an eco-centric as well as anthropocentric perspective, the soil is often considered as a complex ecosystem containing highly valuable resources (Yang et al. 2020). Due to many crucial functions in the ecosystem, the soil is considered as one of the most critical resources. However, woefully the soil health is being degraded at a global scale due to many anthropogenic interferences, among which crop intensification and mono-cropping are most affecting agricultural practices. The important evil soil health has been evolved in terms of its definition over time from focusing about soil quality and production to soil's ability to maintain a range of ecological functions in its appropriate ecosystem, supporting long-term sustainable cropping systems. Thus, soil health is defined as the ability of a soil to function and provide ecosystem services (Thomas et al. 2019, Van Es and Karlen 2019).

While considering anthropogenic interference, considering intensive cultivation of cereal crops to meet the hunger demand of the overcrowded countries has created havoc to the soil health as cereal crops are exhaustive crops, and practices involved in their production are hampering physical properties of soil and thereby aggravating deterioration of overall soil health. Considering the staple food of all over the world, rice and wheat contribute around more than 50%, especially rice in the Asia-Pacific region, including India (Fuhrmann et al. 2019). Furthermore, its demand to feed the population is the only and foremost reason behind the intensive cultivation. As the world's largest agricultural production system RWCS covers not less than 10.3 M ha of the area in India among which 85% falls within IGP (Ladha et al. 2009). Long-term and intensive cultivation of rice affect the soil organic carbon (SOC) dynamics, soil nutrient elements and nutrient use efficiency (NUE) of nutrients which hampers the soil quality as well as productivity (Bhattacharyya et al. 2012; Meetei et al. 2020). A deteriorated soil when being provided as a base for another essential crop wheat which follows rice in a RWCS within a limited period the productivity of wheat is also reduced. Intensive RWCS has led to poor soil health in many aspects and needs keen discussion to overcome the causes of its degradation. Therefore, the reasons behind the deterioration of various aspects of soil health (physical, chemical and biological aspects, Soil fertility and Organic Carbon) which are continuously found to be affected by intensive RWCS is being discussed and listed (Table 19.3).

Table 19.3 Physicochemical properties contributing to soil health as affected by intensive rice-wheat cropping system (RWCS)

Aspects of soil health	Properties affecting soil health	Deleterious effects of intensive RWCS on various soil properties	Reasons behind the effects	References
Physical Aspect	Soil structure	Structural deterioration of soil under intensive RWCS.	Due to puddling (tillage under wet condition)	Kukal and Aggarwal (2003), Behera et al. (2009), Yang et al. (2020)
	Aggregate stability	Macro and Meso aggregates which are considered as an index for carbon sequestration and many physical properties are often broken down to micro aggregates.	Puddling in rice and seedbed preparation operations in both rice and wheat are considered the root cause.	Das et al. (2014), Bhatt (2015), Kumar and Nath (2019)
	Bulk density (BD)	A gradual increase in soil BD have been recorded following rice-based cropping systems mostly in uplands	Results due to reduces overall porosity as a result of puddling practice in rice.	Motschenbacher et al. (2011), Behera et al. (2009)
	Hydraulic conductivity	Hydraulic conductivity is reduced to fulfil the purpose of water stagnation.	As submergence is a prerequisite for most of the rice varieties cultivated over India, puddling practice is done intentionally to reduce the hydraulic conductivity of the soil and produce impermeable subsurface layer.	Behera et al. (2009), Mousavi et al. (2009)
	Underground water table	A precisely reduced ground water level (1 ft. year-^{1}) in northern India	Due to the water-intensive cultivation practices prevailing in these areas. Mostly irrigated rice, which is a heavy water consumer (consumes about 5000 litres of water to produce unit kg of rice).	Soni (2012), Bhatt (2015)
	Surface and subsurface Penetration resistance	Subsurface compaction is prominent after the harvest of rice and results in more penetration resistance and causes difficulty for the wheat crop in	Due to repeated puddling of soil; mainly coarse and medium-textured soil.	Kukal and Aggarwal (2003), Van Es and Karlen (2019), Motschenbacher et al. (2011)

		RWCS by restricting its root growth and aeration stress.		
Chemical Aspect	Redox potential	Redox potential is found to be low in paddy soils.	Due to prolong flooded condition in rice cropping.	Bhatt (2015), Yang et al. (2020)
	Nutrient availability	The reduction in availability of N, S and Zn.	Due to low reduction potential caused due to flooding conditions in rice and many times the deficiency affects wheat crop due to its immediate sowing after rice harvest.	Bhatt (2015), Yang et al. (2020), Mishra et al. (2020)
Biological Aspect	Microbial community	There might be a reduction in the beneficial aerobic microbial community.	The flooded condition restricts the respiration in aerobic microbes due to lack of oxygen as an electron acceptor during the process.	Hurisso et al. 2018, Yang et al. (2020)
	Denitrification	Denitrification rate increases with flooding, which leads to nitrogen loss from soil to atmosphere in the form of oxides of nitrogen.	Due to the application of nitrogenous fertilizer in the reduced layer of the puddled soil. Aerobic microbes utilize the oxygen present in nitrate-nitrogen as an electron acceptor in respiration under the flooded condition and reduce it to atmospheric nitrogen (N_2)	Cao et al. (2020)
	Enzymatic activity	Alkaline Phosphatase Activity (APA) and dehydrogenase activity are found to be affected	As dehydrogenase activity is the measure of active microbial cells present in the soil; their reduction in population due to conventional tillage system and anoxic conditions may be the reason for its reduction. Reduction in APA could be due to heavy phosphatic fertilizer application, which hinders the activity of the enzyme.	Yang et al. (2020)

(continued)

Table 19.3 (continued)

Aspects of soil health	Properties affecting soil health	Deleterious effects of intensive RWCS on various soil properties	Reasons behind the effects	References
	Microbial biomass (MBC)	Microbial biomass carbon and nitrogen reduces gradually	Due to conventional tillage application in most of the areas which expose organic carbon to decomposition hence reduces its quantity gradually followed disturbance in microbial life cycle and reduction in MBC and MBN.	Sainju et al. (2009), Curaqueo et al. (2011), Mishra et al. (2014)
Fertility Aspect	Nutrient balance	Nutrient balance is disturbed in the upper vadose zone of soil under intensive RWCS	As rice and wheat both are cereal crops having an adventitious root system which uptakes nutrients from the surface layer of soil. Hence, their intensive cultivation hampers the nutrient balance of upper vadose zone.	Gill (1992), Sharma et al. (2019b)
	Nitrogen (N) immobilisation	Immobilization of N due to new crop residue incorporation further causes a reduction in crop yield.	The higher C: N ratio of fresh crop residue causes immobilization of N due to its uptake by microbial cells. Hence, pre-incubation of crop residue is necessary before their incorporation.	Yang et al. (2020)
	Micronutrient deficiency	Multiple micronutrient deficiencies both in soil and plants have been observed under intensive RWCS.	Iron and Zinc deficiencies are prevalent in rice whereas, manganese deficiency and selenium toxicity are prevalent for wheat due to exhaustion of their pool due to intensive root growth in the upper layer of soil and their untimely and injudicious application by the resource and	Mishra et al. (2020), Aryal et al. (2015)

			technology poor farmers. Lack of adequate soil testing facilities.	
Organic Matter	Organic carbon	Oxidation of hidden organic carbon once present in macro and meso aggregates.	Due to the destruction of the aggregate structure resulting from various agricultural practices involved in intensive RWCS.	Roper et al. (2013), Das et al. (2014), Kumar et al. (2019)
	Carbon stability	Carbon stability is reduced under intensive RWCS under conventional tillage and puddling practices	More than 50 per cent of most of the sequestered carbon is aggregate carbons stored in macroaggregates which get destroyed by conventional tillage practices.	Choudhary et al. (2014), Nath et al. (2017), Kumar and Nath (2019), Kumar et al. (2019)
	Lability index (LI)	Labile carbon is considered as an active pool of carbon which is readily available and one of the critical fraction for the crop as well as microbial uptake. The fraction of labile carbon in total organic carbon is the LI which is found to be reduced under conventional tillage system.	Soil structure deterioration, reduction in aggregate stability and destruction of macroaggregates could be the reasons.	Parihar et al. (2016); Nath et al. (2017); Kumar and Nath (2019)

19.3.2 Nutrient Exhaustion: Threat Towards Sustainability of RWCS

IGP mostly grows rice and wheat year after year due to demand of its fertile soil and ever-increasing population moreover, as both the rice and wheat crops are higher in biomass due to their proliferous growth and their adventitious root, which withdraws maximum of the essential nutrients from topsoil reserve and due to continuous cultivation (less gap between crop); as a result, soil gets less time to recover its nutrients back. Its contradictory that except the grain all other parts of rice are not suitable for consumption and can be returned to the soil again after their harvest to replenish the nutrient pool but again due to less time gap between crops in RWCS in IGP the resource-poor farmers prefer to burn the residue in situ which aggravates many environmental problems including nutrient loss because the burning of crop residues are depleting more than 80% N, nearly a quarter of both P and K and half of S present in them (Jain et al. 2014). Another problem is arising due to faulty nutrient application methods to replenish soil reserves for crop growth where removal exceeds replenishment by fertilizers; blanket dose recommendation is one bright example where there is less nutrient use efficiency (Timsina et al. 2006). Many reports also suggest the sharp decline in organic carbon reserve in north-western India, which is a drawback of inappropriate use of fertilisers (Singh et al. 2007; Majumder et al. 2008; Jain et al. 2014). Therefore, it could be summarised that faulty fertilizer application practices along with improper crop rotation and injudicious management of residue after crop harvest are causing nutrient exhaustion in soils of India.

19.3.3 Global Warming Gas Emission and Mitigation Potential of RWSC

Global warming potential (GWP) is directly related to the increase in greenhouse gases (GHGs) in the atmosphere and is measured in terms of carbon dioxide equivalent (CO_2- eq) (Gupta et al. 2015). The agriculture sector has reported for higher contribution in gases GHGs, nearly 24% of global GHG emission (IPCC 2014). As per reports, Indian agriculture is contributing 17% of total anthropogenic GHGs emission in the country (INCCA 2011). The adoption of intensive RWCS over the IGP has led to the rise of many GHGs in the atmosphere, mostly methane (CH_4) and nitrous oxide (N_2O) due to heavy application of irrigation and fertilizers. Contribution of India among Four other South Asian countries in terms of total CH_4 (Tg CH_4 Year^{-1}) and nitrous oxide (Gg N_2O Year^{-1}) emission from rice fields is depicted in Fig. 19.4.

Due to higher agricultural practices Indian rice fields covering 42.21 million ha are found to be emitting 2.07, 0.02, and 72.9 Tg of CH4-C, N2O-N and CO2-C, respectively, with a global warming potential (GWP) of 88.5 Tg CO2-C eq. Annual GHG emission from 28.08 M ha of wheat-growing areas is found to be 0.017 and 43.2 Tg of N2O-N and CO2-C, respectively, with a GWP of 44.6 Tg CO2-C eq (Bhatia et al. 2012a). Many studies have been carried out on the contribution of the

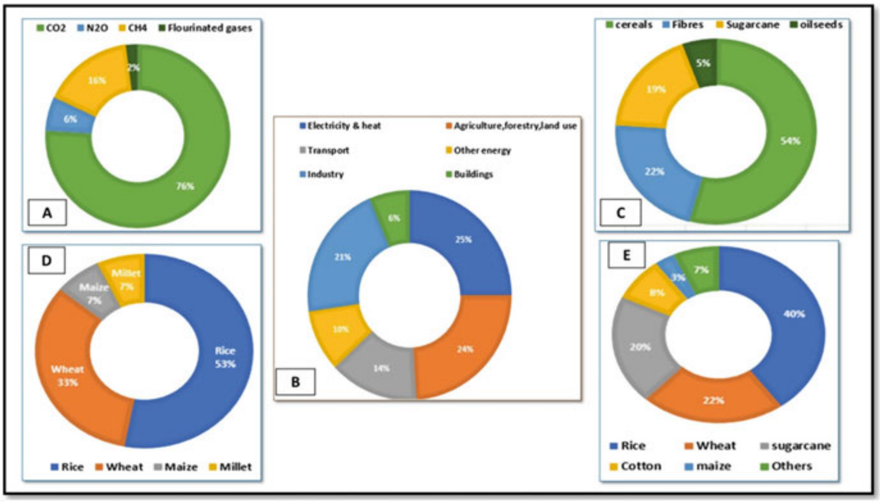

Fig. 19.4 Facts regarding the gradual contribution of Rice and Wheat crops towards various greenhouse gas (GHG) emission: (**a**) contribution of various GHGs towards global warming in India, (**b**) contribution of agriculture sector towards anthropogenic GHGs emission in India, (**c**) contribution of various crops towards crop residue burning, (**d**) contribution cereal crops especially towards crop residue burning, (**e**) contribution of rice and wheat towards GHGs emission among other major crops cultivated in India (Adapted from INCCA 2011, IPCC 2014, FAOSTAT 2014)

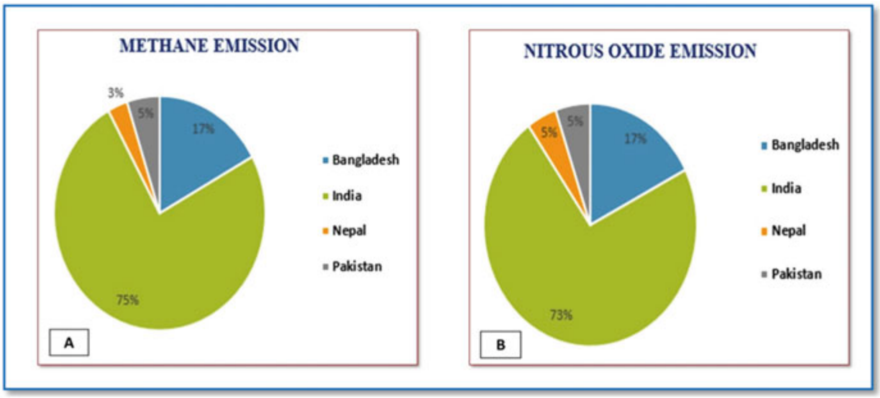

Fig. 19.5 Emission of Methane (Tg CH_4 $Year^{-1}$) and nitrous oxide (Gg N_2O $Year^{-1}$) from rice fields in South Asia Sources (Adapted from Sapkota et al. 2018)

rice-wheat cropping system on GWP, but very few have quantified it (Bhatia et al. 2012b; Gupta et al. 2015). Compiling various studies on GHG emission and global warming (INCCA 2011; IPCC 2014; FAOSTAT 2014) the gradual contribution of rice and wheat crop alone among all other major crops is being presented in various pie charts in Fig. 19.5. As it is already being discussed about the faulty management practices in RWCS of IGP mainly residue burning is positively contributing to carbon dioxide (CO2) emission to the atmosphere along with many GHGs hence, contributing to GWP of the system

19.3.4 The Pattern of Carbon Footprints in RWCS

Carbon footprint (CPF) in agriculture is referred to the amount of GHGs emitted in terms of carbon equivalent (C-eq) resulting from various agricultural practices (Jaiswal and Agrawal 2020). As the reasons and scenario of GHG emission from various agricultural activities have already been discussed in the previous section, we can draw conclusion regarding the CPFs of various GHGs due to faulty agricultural practices. In contrast to earlier time when CO_2 was solely considered responsible for carbon footprints; in recent days, all major harmful GHGs viz. CO_2, CH_4, and N_2O are revealed to contributing towards carbon footprints in terms of CO_2 equivalent (CO_2-e) among which CH_4 is significant contributor followed by CO_2 and N_2O (Ravindra et al. 2019). IPCC (2014) has defined CO_2-e as CO_2 concentration that would cause the same radiative forcing as a given mixture of CO_2 and other forcing components. The carbon footprint from agriculture is calculated by the following formula (Lal 2004).

Carbon footprint = ($\sum$Agricultural input $*$ GHG emission coefficients) / (Grain yield).

Therefore, the factors influencing GHGs emission are the factors influencing CPF in agriculture. This rigorously cultivated RWCS of the IGP plays a significant role in food security and is a potential source of greenhouse gas (GHG) emission. Quantification of the carbon footprint of this cropping system can help assess the GHG emission due to crop production along with identification of low carbon options to improve the sustainability of the cropping system. Quantification of CFP will help in increasing awareness towards the changing climate and helping scientists for juxtaposing the effect of different crop management options on the environment. There is a need to develop low C intensive technologies for maintaining the sustainability of RWCS.

19.4 Innovative Pathways to Enhance NUE

In the rice-wheat cropping system (RWCS), fertilizer use is highly variable across the agro-climatic regions of India (Singh et al. 2013; Sharma 2003). The rice and wheat are heavy feeders and nutrient-exhaustive crops (Hegde and Dwivedi 1992; Shweta and Malik 2017). The amount of nutrient applied through external sources could not maintain the balance between nutrient supply from the soil and crop removal, causing a decline in soil fertility. Of the total applied nutrients in the soil, the NUE of N, P, K, S and micronutrients vary from 30–50, 15–20, 70–80, 10–30 and 1–5%, respectively, that might be due to immobilization, volatilization, denitrification, leaching, fixation etc. Therefore, application of nutrients based on the principle of soil test crop response (STCR) and 4R Nutrient Stewardship could help in enhancing the nutrient use efficiencies and sustain the productivity and soil health.

19.4.1 Role of CA in Improving Nutrient Use Efficiency (NUE) in RWCS

When applied practically, the principles of CA attribute to several prudent functions. Negligible soil disturbance improves soil physical structure and soil biota by minimising mechanical pressure of cultivation. A permanent soil covers via retention of crop residues increases water infiltration, reduces evaporation, water runoff and soil erosion for maintaining soil fertility and productivity by ensuring shielding effect on impact of raindrops (Bhatt and Kukkal 2014; Jat et al. 2018). Soil temperature is regulated due to residue retention; also it improves soil organic matter content of top soil due to its decomposition in soil following incorporation. A solitary principle of CA may be executed by employing several practices. CA can ensure minimal soil disturbance due by utilising NT seeding and could cover soil surface via application of mulches of either live cover crops or dead biomass (Kumar et al. 2018c). CA does not opposes the use of mineral fertilisers, but it implies and recommends good agronomic practice in which mineral fertilisers which are affordable to farmers are applied judiciously. Rather, proper nutrient management is the main highlight behind the practice of CA than only fertiliser use.

Conservation agriculture contribute in a considerable amount in increasing the fertilizer use efficiency of the rice-wheat systems in multifaceted ways by favourable management of the soil environment and crop systems for better nutrient retention in soil and its absorption and subsequent assimilation in plants. CA aids in improving nutrient use efficiency by its ability to prevent nutrient loss by bringing down soil erosion rate in field level (Jat et al. 2018). Though suitable utilisation of deep-rooted cover crops having ability to recycle leached nutrients and via reducing run off from top soil layer CA is the best option till date to minimise nutrient loss in fields. Thereby ensuring greater availability of both native and applied nutrients in adequate amounts to the crops. Conservation agriculture can result in improved use efficiency of fertilisers by more than 10% in the rice-wheat system, mostly attributed to the better placement of fertilizer with the seed drill as opposed to broadcasting with the traditional system (Hobbs and Gupta 2003). According to some reports, lower N fertilizer efficiency might be recorded as a result of microbial immobilization due to maintenance or application of crop residues, which can be a short term effect. In contrast, enhance nutrient cycling is observed in long term practices with time due to population and activity of potential microbes. An improved soil aggregation and soil organic matter content results from residue decomposition which further leads to a better nutrient as well as water use efficiency of the system (Yang et al. 2020). However, the selection and use of different plants as cover crops or residues and its effects on the main crop and the nutrient dynamics in the soil due to decomposition of residues needs some thorough studies with experimental backing. Reports suggests reduction in P sorption due to blockage of the adsorption sites by organic matter and low molecular weight compounds viz. oxalate and malate, but these effects might be transient (Fontes et al. 1992; Bhatti et al. 1998).

Humic substances can be more efficient as compared to low-molecular-weight organic acids because of their persistence and higher stability in agricultural soils. Inclusion of legumes in conservation agriculture can lead to greater nutrient availability to plants. Highest levels of exchangeable K, calcium (Ca), and magnesium (Mg) were found in systems with pigeon pea and lablab (*Dolichos lablab*) and lowest in systems including clover (Burle et al. 1997). Similarly, Govaerts et al. (2007) observed higher C, N K, and lower sodium (Na) with residue retention in the system as compared to residue removal in a rainfed permanent raised bed planting system in the subtropical highlands of Mexico. However, in some cases, the increased infiltration as a result of stubble retention may cause deep percolation and increased leaching of mobile nutrients, which may counterbalance advantages of retaining them in situ (Erenstein 2002; Scopel et al. 2004). However, it still stands as a very viable option for increasing the nutrient retention in the soil system and its subsequent absorption by the plant system.

At last, it can be inferred that adequate nutrient supplies as well as acceptable agronomic practices are essential components of any agricultural management system. Conservation agriculture disregarding adequate nutrient management holds lesser good in reality. The concepts conservation agriculture and integrated nutrient management should be promoted and practised simultaneously in a flexible manner for the greater good of the agricultural system and the farming community.

19.4.2 Soil Test Crop Response (STCR) Based Fertilizer Recommendations

There are different methodologies to evaluate and quantify the supply of balanced nutrients to the crops, i.e. through soil test rating, estimation of critical limit and fertility gradient approach. Ramamoorthy et al. (1967), in India, established the theoretical basis and experimental proof for the Liebig's law of minimum which operates equally well for N, P or K. Sufficiency concept of Mitscherlich and Baule concept indicates that the relationship between grain yield and uptake of nutrients is linear. This implies that for obtaining a given yield, a definite quantity of nutrients must be taken up by the plants. Application of nutrients based on soil test improves the response ratio and benefit: cost ratio in comparison to the nutrients applied based on the magnitude of the deficiency and blanket application (Rao and Srivastava 2000; Singh et al. 2017). Thus, once this is known, the fertilizers that needed to be applied can be estimated by taking into account the efficiency of available nutrients contribution from the soil and the efficiency of uptake from applied fertilizer nutrients towards total uptake of the nutrient. This forms the basis for fertilizer recommendation for a targeted yield of a crop. For formulating fertilizer recommendation at a given yield target for a given soil type, crop and agro-climatic conditions- (1) Nutrient requirement (NR) in kg/q (2) The per cent contribution from soil available nutrient to total uptake (CS) (3) The per cent contribution from the applied nutrient in terms of fertilizer to the total uptake (CF) (4) The per cent contribution from the applied nutrient in terms of manure to the total uptake (CC) is to be recorded from field experiments. Based on these data, targeted yield equations under simple or integrated nutrient management as per the procedure described by Ramamoorthy and Velayutham (1971) were calculated as below.

$FN = (NR/CF) \times 100 \times T) – (CS/CF) \times SN – (CC/CF) \times CN.$

$FP_2O_5 = (NR/CF) \times 100 \times T) – (CS/CF) \times SP_2O_5 – (CC/CF) \times CP_2O_5.$

$FK_2O = (NR/CF) \times 100 \times T) – (CS/CF) \times SK_2O – (CC/CF) \times CK_2O.$

Where, T is yield target (q/ha), SN, SP_2O_5 and SK_2O are available soil N, P_2O_5 and K_2O (kg/ha), respectively, while, CN, CP_2O_5 and CK_2O are the amounts of N, P_2O_5 and K_2O applied through organic manures (kg/ha), respectively,

Soil test based rates of fertilizer application helped to obtain higher response and benefit: cost ratios (Dey and Srivastava 2013). It was evident from the trials conducted over a wide range of agro-ecological regions, STCR based approach of the nutrient application over generally recommended dose (GRD) of nutrients and farmers' practice (FP) has a definite advantage in terms of increasing nutrient response ratio, net profit and benefit-cost ratio over the general recommended dose of nutrient application (Table 19.4).

19.5 4Rs Nutrient Stewardship: Concept and Application

Fertilizer selection depends on different factors like nutrient requirements by the crops, inherent soil supplying capacity, soil type, climate conditions, availability in the market, price etc. Optimum soil fertility-induced plant nutrition has a crucial role in maximizing yield and quality production of RWCS. The 4R Nutrient Stewardship, a new innovative approach, helps in best management practices for the nutrients and defines the right nutrient source, at the right rate, right time, and the right place for fertilizer application (Mikkelsen et al. 2009; Phillips et al. 2009; Sharma et al. 2019a, b, c). Bruulsema et al. (2009) first introduced this concept. The 4Rs, i.e. right source, rate, time, and place, are interlinked with each other and cannot be separated (Table 19.5).

19.5.1 Right Source

The selection of the right source of fertilizer depends on crop needs, soil properties, availability in the local market, application equipment and economics etc. The proper use of enhanced efficient fertilizers (those that increase nutrient availability/ uptake and decrease losses to the environment compared with a reference fertilizer) can offer a variety of benefits like increased yields, reduced fertilization rates, and multiple environmental benefits (Trenkel 2010). Urea is a prevalent, cheaper and preferable source of N among the farmers, but its imbalanced application causes the loss of N through leaching, runoff, volatilization. In alkali soils (pH 7.0–7.5) ammonium fertilizers are superior over nitrate fertilizers because it acts as a soil

Table 19.4 The response ratio and economics of existing and improved nutrient management technologies in rice, wheat and maize crops in different soils of Bihar

Treatments	Response (kg/kg)	Net profit (INR/ha)	B: C ratio
Paddy (mean of 19 trials)			
FP	4.83–14.70 (8.74)	2560–14,753 (6731)	1.15–5.92 (3.06)
GRD	6.05–13.90 (9.63)	4615–16,805 (9301)	1.71–5.16 (3.49)
STCR-YT 30 q/ha	11.28–18.60 (13.83)	7772–16,556 (11807)	4.55–8.41 (5.85)
STCR-YT 40 q/ha	7.76–12.40 (9.57)	8965–19,766 (12891)	2.36–5.41 (3.59)
STCR-YT 40 q/ha (IPNS)	7.53–15.40 (10.56)	7616–21,052 (11822)	1.72–4.90 (2.94)
STCR-YT 45 q/ha (IPNS)	7.33–8.05 (7.62)	9453–10,465 (9834)	1.77–2.03 (1.88)
Wheat (mean of 21 trials)			
FP	7.31–19.60 (10.26)	5926–31,900 (12356)	2.68–12.80 (5.37)
GRD	8.18–14.00 (10.22)	9000–36,215 (15196)	2.90–12.00 (5.37)
STCR-YT 30 q/ha	14.78–19.55 (17.00)	8795–13,385 (10587)	6.92–10.08 (8.74)
STCR-YT 35 q/ha	13.30–18.60 (15.03)	29,819–33,019 (31278)	11.50–18.90 (14.10)
STCR-YT 40 q/ha	9.84–20.35 (13.82)	13,157–38,001 (19526)	4.07–14.80 (7.81)
STCR-YT 45 q/ha	9.19–17.66 (12.80)	15,386–21,022 (17697)	3.41–10.58 (6.32)
STCR-YT 30 q/ha (IPNS)	23.18–27.50 (24.74)	8642–11,196 (9869)	5.09–5.84 (5.45)
STCR-YT 35 q/ha (IPNS)	14.80–22.40 (18.68)	30,035–33,020 (31671)	8.70–13.70 (10.93)
STCR-YT 40 q/ha (IPNS)	11.73–19.50 (15.12)	13,563–38,157 (24137)	3.70–12.00 (6.69)
STCR-YT 45 q/ha (IPNS)	10.43–20.24 (14.68)	16,025–21,453 (18101)	3.55–8.07 (5.59)

FP = farmers' practice, GRD = General Recommended Dose, STCR-YT = Soil Test Crop Response-Yield target, IPNS = Integrated Plant Nutrient Supply

acidifier. However, in calcareous soils (pH > 7.5) ammonical fertilizers should be preferred because its application could not alter the pH due to high buffering capacity provided by $CaCO_3$ (Hagin and Tucker 1982).

19.5.2 Right Rate/Dose

Excess and unbalanced application of fertilizer may either lead to losses or mining of nutrients, and low quality produces. Thus, the rate of fertilizer should be decided very precisely considering indigenous nutrient supplying capacity of the soil, crop requirement, target yield and environmental factors. The nutrient release pattern from organic sources should also be taken into consideration. In general, soil test values are used for fertilizer recommendations. However, some nutrient decision support tools like Rice Crop Manager (RCM) could also be used for fixing the rate of the nutrients.

Table 19.5 The critical scientific and associated practices of 4R principles

	Source	Rate	Time	Place
Examples of vital scientific principles	✓ Ensure a balanced supply of nutrients. ✓ Suits to soil properties.	✓ Assess nutrient supply from all sources and inherent nutrient supplying capacity of soil. ✓ Assess crop demand.	✓ Assess the dynamics of crop uptake and soil properties. ✓ Determine the timing of loss risk.	✓ Recognize crop rooting patterns. ✓ Manage spatial variability.
Examples of practical choices	✓ Commercial fertilizer. ✓ Livestock manure. ✓ Compost. ✓ Crop residue.	✓ Test soils for nutrients. ✓ Calculate economics. ✓ Balance crop removal.	✓ Pre-plant. ✓ At planting. ✓ At flowering. ✓ At fruiting.	✓ Broadcast. ✓ Band/ drill / inject.

(Modified from Richards Meryl et al. 2015)

19.5.3 Right Place

Fertilizers must be placed near the root zone so that plant could take optimum nutrient (Murrell et al. 2009). The fertilizer placement should be decided based on rooting patterns, soil properties, and available technology. Band application of fertilizer is generally preferred for improving nutrient use efficiency. For example, nitrogenous fertilizers should not be placed on the soil surface for prolonged periods, especially in alkaline soils, because there is a chance of volatilization loss of nitrogen.

19.5.4 Right Time

The application of nutrient at the right time ensures their adequate supply during peak uptake and critical growth stages. The fertilizer application at the right time also helps in reducing nutrients loss into the environment and ensures the supply as per crop demand. Application timing is generally site-specific and governed by local environmental conditions and management practices being followed by the farmers. The different tools like Soil Plant Analysis Development (SPAD), Green Seeker and Leaf Color Chart (LCC) could be used to assess the demand and remediation of N in standing crop.

19.6 Conclusion and Future Prospects

A paradigm shifts from extensive high chemical input conventional rice-wheat cropping to intensive optimum input site-suited conservation/regenerative agriculture is the need of the hour to catalyse crop productivity, profitability and environmental safeguard. Wider adoption of climate resilient practices need to be addressed to cater high out per input, GHG reduction, improving soil health and livelihood of the farmers. In last 2 decades' extensive research has been done on CA in South Asia, there is a need to bottom neck the knowledge and map the strategy considering soil, climate, cropping systems and socio-economic conditions. All the principles of conservation agriculture (CA) may not be applicable and workable for all the environment considering the variability and farmer's mind-set at farm scale, therefore best fit strategy need to be implemented at initial stage and later all principles may be used. In India, it was evidenced that even after 10 years of CA, there was no significant changes in organic carbon content, therefore, strategic tillage may be employed and geared based on local environment and soil conditions. Common consensus among the diverse researchers, service providers, other stakeholders and farmers need to be streamlined to scale CA for reaping benefits. Gathering and translating what works and what not in RWCS as lessons and science to ensure better management and setting long-term goals keeping SDG in view. Precision agriculture and best bet resource conservation technologies need to be translated into ICT based tools for scaling out innovative technologies. Inclusion of 4Rs nutrient stewardship with site specific modalities is the essence of innovative pathways for nutrient use efficiency. Visioning and visualizing the present and future threats and plausible solutions aid to AI and digital innovations is the key to climate resilience and sustainability. In nutshell, a holistic approach need to be propagated by understanding the present needs and future thrust and developing a framework involving multi-stakeholders and policymakers to map the areas of priorities for improving NUE and optimising fertilizer application rate for reducing environmental footprints.

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Integrated Weed Management in Wheat and Barley: Global Perspective

20

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20.1 Introduction

Wheat and barley are the major cereal crops grown in about 220 and 70 million hectare (mha) globally with average production of 763.06 and 160 million tons (mt), respectively. The assured production and supply of wheat and barley is essential for global food security. These two crops are grown as both winter and spring crops (Table 20.1) depending upon the location, weather conditions and major cropping system adopted. Spring wheat is cultivated over regions with mild winter and sown in either winter or autumn and harvested in spring/summer season without vernalization requirement. While, winter wheat is grown in the autumn season (typical harsh winters) remains in field to fulfill its vernalization requirement (Baker et al. 1986), longer in duration and harvested in following summer season. Due to longer duration in field, winter wheat yields more than spring wheat. Also, in some areas such as United States, spring barley is grown as rotational crop with winter wheat.

Global human population is escalating at an unprecedented rate and hence the pace of the global food production needs to match this decline in per capita availability and associated risks like economic and social disturbances. Weeds are the important factor in reducing the world's eight most important food and cash crops production by 13.2% at global scale (Oerke 2006). In India alone, this figure stands at USD 11 bn with USD 3.3768 bn in wheat alone after rice (USD 4420 million). However, location, crop and soil types significantly influence the actual

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Table 20.1 Major wheat producing regions/countries (2019)

Countries	Area		Production		Major producing regions
	million ha (m ha)	world %	million tons (m t)	world %	
China	23.7	11.0	133.6	17.4	North-East China (Beijing and Manchurian plain), South-East China (Human and Yangtze fertile plain) for spring wheat, North China Plain and Kaoliang Region for winter wheat and Hwang Ho valley
India	29.3	13.6	103.6	13.5	Spring wheat in states of Punjab, Haryana, Madhya Pradesh, Uttar Pradesh, Bihar, Rajasthan, Gujarat and Maharashtra during *rabi* season
Russia	27.6	12.8	74.5	9.7	Both winter and spring wheat in black soil region, large areas of the Steppes stretching from the Dnieper into Asiatic
USA	15.6	7.2	52.3	6.8	Hard red spring (HRS) wheat (Montana, Minnesota, South and North Dakota), winter hard red wheat (Kansas, Nebraska, Oklahoma, Missouri, and Northern Texas), soft red (Illinois, Indiana, Ohio, Pennsylvania), soft white (lakes of Michigan and Huron along with California and Columbia plateau region)
Canada	9.66	4.5	32.3	4.2	Saskatchewan, Ontario, British Columbia Alberta and Manitoba province along with Canadian Prairies
Total world	215.9		765.8		

Source: FAO, 2021

yield losses due to weeds at farmers' fields (Gharde et al. 2018). In wheat growing zones of India, weed results an average yield loss of 20–32% and losses are comparatively higher in North Western Plains Zone, North Eastern Plains Zone, and Northern Hills Zone than Peninsular and Central Zone (Mongia et al. 2005; Chhokar et al. 2012).

Moreover, repeated use of same herbicide and mono-cropping leads to weed flora shift, herbicide resistance evolution in major weeds of wheat and further putting pressure on sustainable wheat production. Due to multiple resistance development in *Alopecurus myosuroides* in England, the annual resistance cost is estimated as £0.4 bn due to annual wheat yield loss of 0.8 mt. Similarly, loss in wheat due to resistance of a single weed, *Phalaris minor* in Punjab and Haryana states of India is estimated $550 mn annually. While, as per total economic loss of herbicide control against black-grass, the annual cost could be £1 bn with yield loss of 3.4 mt (Varah et al. 2020). Preventing herbicide resistance is comparatively easier and more profitable than overcoming resistance. Weeds are not only known to reduce crop yield but also impact the crop quality and increased environmental pollution due to repeated application of herbicides owing to faulty spray techniques and weather conditions. Therefore, there is a need to devise efficient weed control practices for wheat and barley.

20.2 Yield Losses in Wheat and Barley

The spatial-temporal crop weed competition is significantly affected by agronomic and crop management factors such as nature of crop and varieties, crop cultivation practices and climatic factors. Consequently, yield loss also depends on nature of weed species (Table 20.2) infesting, weed density, dry matter accumulation, weed and crop emergence timing, nature of crop cultivar, planting density, field moisture at the time of crop sowing, types of cropping and tillage system, (Malik and Singh 1995; Singh et al. 1999; Chhokar and Malik 2002; Xu et al. 2011, 2019; Om et al. 2004, 2005). Among these factors, weed density, time of weeds emergence, agronomic practices, and weed species type have major influence on the crop-weed competition. Weeds that emerge simultaneously/before the crop show more competitiveness than weeds emerging after crop establishment. The crop-weed competition duration and intensity level determine the extent of yield losses in crops (Swanton et al. 2015). However, yield loses in barley were comparatively lower as compared to pea and canola (Harker 2001). In winter wheat, the competitive order based on relative yield loss was *Avena fatua* > *Matricaria perforata* > *Galium aparine* > *Myosotis arvenis* > *Poa trivialis* > *Alopecurus myosuroides* > *Stellaria media* > *Papaver rhoeas* > *Lamium purpureum* > *Veronica persica* > *Veronica hederifolia* > *Viola arevensis* (Wilson and Wright 1990). The thresholds for site-specific weed control for *Galium aparine*, *Alopecurus myosuroides* and other broad-leaved weeds were 4, 48 and 12 plants m^{-2}, respectively (Keller et al. 2014). Blessed milkthistle (*Silybum marianum*), a noxious weed in Pakistan should be controlled within 1 to 5 week after emergence (Rehman et al. 2019) as its density of >5 plants m^{-2} results in significant reduction in effective tillers m^{-2} (18–20%), no of grain/spike (23–26%), grains weight (28%) leading to grain yield reductions up to 30% (Rehman et al. 2020). In Iran, the economic threshold of *Avena ludoviciana*, *Convolvulus* spp., *Salsola kali, Chenopodium album* and *Rapistrum rugosum* in wheat was reported as 5, 12, 13, 19, and 27 plants m^{-2}, respectively (Gherekhloo et al. 2010). Galon et al. (2019) studied critical period of control for ryegrass and revealed that management methods must be implemented within 11–21 days after crop emergence. Grain yields of wheat and triticale were reduced by about 50% due to *P. minor* competition (Dhima and Eleftherohorinos 2003). The mixture of *Emex australis* and *E. spinosa* (1,1) with wheat caused grain yield reduction by 63–72% (Javaid et al. 2016). Diverse crop rotations with inclusion of clover–grass leys, spring crops and intensive tillage reduced the infestation of *A. myosuroides*. Preventive methods could be based on rotations of winter cereals and spring crops with less clover–grass leys (Gerhards et al. 2016). Barley yield was reduced by 25% with

Table 20.2 Wheat yield losses caused by different weeds in wheat in various countries

Location/ region	Weed	Weed density	Grain yield reduction	References
Argentina	*Lolium multiflorum*	100 m^{-2}	20–30%	Scursoni et al. (2012)
Argentina	*Avena fatua*	100 m^{-2}	20%	Scursoni et al. (2011)
Australia	*R. raphanistrum*		3–18%	Eslami et al. (2006)
Chile	*Avena fatua*	3 m^{-2}	3.5–4.5%	Pedreros (2001)
Chile	*Lolium multiflorum*	10 m^{-2}	1.3–1.6%	Pedreros (2001)
China	*Descurainia sophia*, *Capsella bursapastoris*		13–20%	Han et al. (2014)
Germany	*Stellaria media, Veronica persica*, *Capsella bursa pastoris*, *Lamium purpureum*		1.2 kg ha^{-1} $plant^{-1}$ m^2.	Keller et al. (2014)
Germany	*Galium aparine*		17.5 kg ha^{-1} $plant^{-1}$ m^2.	Keller et al. (2014)
Germany	*Alopecurus myosuroides*		12.4 kg ha^{-1} $plant^{-1}$ m^2.	Keller et al. (2014)
Germany	*Matricaria chamomilla*		1.9 kg ha^{-1} $plant^{-1}$ m^2	Keller et al. (2014)
India	*Phalaris minor*	200 m^{-2}	24–32.6%	Duary and Yaduraju (2006)
India	*Phalaris minor*	15 m^{-2}	14%	Kaur et al. (2012)
India	*Phalaris minor*	400 m^{-2}	42–44%	Yadav (2002)
India	*Phalaris minor*	1000–2000 m^{-2}	80–100%	Malik and Singh (1995) Singh et al. (1999) Chhokar et al. (2019)
India	*Rumex spinosus*	30 m^{-2}	46%	Buttar et al. (2017)
Iran	*Sinapis arvensis*L.	15 m^{-2}	22.1–43.1%	Behdarvand et al. (2013)
Iran	*Avena Ludoviciana* L.	75 m^{-2}	26.3–30.3%	Behdarvand et al. (2013)
Iran	*Sinapis Arvensis* L	5–15 m^{-2}	21.4–40.2%	Behdarvand et al. (2012)
Iran	*Phalaris minor*	5–20 m^{-2}	12.2–23%	Mansoori (2019)
Iran	*Sinapis arvensis*	16 m^{-2}	18%	Siyahpoosh et al. (2012)

(continued)

Table 20.2 (continued)

Location/ region	Weed	Weed density	Grain yield reduction	References
Jordan	Wild oat	50 m^{-2}	11%	Duwayri and Saghir (1983)
Nepal	Miscellaneous weeds		33%	Joshi (1996)
Pakistan	*Phalaris minor*	40 m^{-2}	28–34%	Hussain et al. (2015)
Pakistan	*Silybum marianum*		20.5%	Rehman et al. (2019)
Pakistan	*Avena fatua*	5–40 m^{-2}	78%	Umm-E-Kulsoom (2018)
Pakistan	*Avena fatua* L.	5–40 m^{-2}	20–76%	Umm-E-Kulsoom and Khan (2015)
Pakistan	*Rumex dentatus*	5–40 m^{-2}	60%	Umm-E-Kulsoom (2018)
Pakistan	*Emex australis*		44–62%	Javaid et al. (2016)
Pakistan	*Emex spinosa*		56–70%	Javaid et al. (2016)
Pakistan	*P. annua*, *Coronopus didymus*, *R. dentatus*, *P. minor*, *Medicago denticulata*		76%, 10–75, 55%, 28%, 23%, respectively	Siddiqui et al. (2010)
Pakistan	*Silybum marianum*	5 m^{-2}	30%	Rehman et al. (2020)
Pakistan	*Galium aparine* L.	8 m^{-2}	24–32%	Aziz et al. (2009)
Pakistan	*Silybum marianum*	3–18 m^{-2}	6–17%	Khan and Marwat (2006)
Turkey	*Alopecurus myosuroides*	20 m^{-2}	19–25%	Mennan and Isik (2004)
Turkey	*Avena spp*	20 m^{-2}	13–19%	Mennan and Isik (2004)
Turkey	*Avena spp*	10 m^{-2}	8.7%	Mennan et al. (2003)
Turkey	*Alopecurus myosuroides*	10 m^{-2}	4.9%	Mennan et al. (2003)
Turkey	*Sinapis arvensis*	32 m^{-2}	36.9%	Mennan (2003)
United Kingdom	*Alopecurus myosuroides*	25 m^{-2}	10%	Finch et al. (2017)
USA	*Avena fatua*	285 m^{-2}	>50%	Stougaard and Xue (2005)

(continued)

Table 20.2 (continued)

Location/ region	Weed	Weed density	Grain yield reduction	References
USA	*Sinapis alba*		28%	Kolb et al. (2012)
USA	*Lamium amplexicaule*	82-155 m^{-2}	13–38%	Conley and Bradley (2005)
Wales	*Phalaris minor*		29%	Iqbal and Wright (1997)
Western Australia	*Bromus diandrus* and *Lolium rigidum*		36% and 11%, respectively	Borger et al. (2020)

70 plants m^{-2} of wild oats (*Avena fatua*) and mainly due to competition from the early emerged (0–35 days after crop emergence) wild oat (Scursoni and Satorre 2005). Weeds not only compete with wheat, but also usurp a large quantity of nutrients and moisture (Singh et al. 1999). Moreover, emergence of several grassy weeds in wheat in northern India (*P. minor, Avena ludoviciana* and *Polypogon monspeliensis*) in 2–3 flushes has complicated their management strategy. A broad understanding of weed-crop competition is required to develop cost-effective and sustainable weed management programme. Further, weed species also act as alternative hosts for insects and diseases. Suproniene et al. (2019) reported that out of 57 weed species, 71.9% harboured *F. graminearum* isolates that is main causal organism of wheat *Fusarium* head blight. Moreover, barberry (*Berberis vulgaris*) a weed species is the prime alternate host for the wheat stem rust fungus.

20.3 Nature of Weed Flora (Country/spp. Based) Associated with Wheat and Barley

Wheat and barley crops are infested by different groups of weeds viz., grass, sedges and broad- leaved weeds (Table 20.3).

20.4 Biology/Ecology/Botanical Characteristics of Herbicide Resistant Weeds

The understanding of weed biology and ecology is required for sustainable weed control as it gives first-hand knowledge about weed, its nature of propagation, crop competition, level of infestation, dispersal and germination mechanism (Table 20.4).

Italian ryegrass (*Lolium multiflorum* Lam.) is a troublesome weed of cereal crops (Bararpour et al. 2017, 2018). It infests about 50% of the wheat acreage in Argentina and its control with selective grass herbicides account for a significant proporation of total cost of production (Scursoni et al. 2012). Italian ryegrass seed persistence

Table 20.3 List of important weeds in wheat and barley (globally)

Country/ region	Important weed flora	References
Argentina	*Avena fatua* L.; *Lolium multiflorum* Lam., *Chondrilla juncea* L., *Diplotaxis tenuifolia* (L.) DC., *Centaurea solstitialis* L. *Rapistrum rugosum* (L.) All., *Stellaria media* (L.) Vill. *Ammimajus* L., *Veronica arvensis* L., *Chenopodium album* L.	Scursoni et al. (2011), (2014), Martinez-Ghersa et al. (2001)
Australia	*Avena ludoviciana* Durieu; *Avena sativa* L.; *Conyza bonariensis* (L.) Cronquist; *Lolium rigidum* Gaudin; *Raphanus raphanistrum* L.	Walker et al. (2002), Vandeleur and Gill (2004), Lemerle et al. (2004), Eslami et al. (2006), Walker et al. (2013)
Bangladesh	*Chenopodium album L.; Cynodon dactylon* L.; *Cyperus rotundus* L.; *Polygonum orientale* L.; *Rumex maritimus* L.;*Vicia sativa L.*	Islam et al. (2018)
Bhutan	*Chenopodium* spp.; *Galinsoga parviflora* Cav; *Persicaria runcinata* (D. Don) H. Gross; *Phalaris minor* Retz.	Mann and Hobbs (1988)
Canada	*Avena fatua* L.; *Bromus tectorum* L.; *Descurainia sophia* (L.) Webb exPrantl; *Hordeum jubatum* L.; *Thlaspi arvense* L.	Ross and Van Acker (2005), Blackshaw et al. (2005), Blackshaw et al. (2000a, b)
China	*Aegilops squarrosa* L.; *Aegilops tauschii* Coss.; *Alopecurus japonicus* Steud.; *Ammannia baccifera* L., *Arenaria serpyllifolia* L.; *Avena fatua* L.; *Bromus japonicus* Thunb.; *Calystegia hederacea* Wall.; *C. sepium* (L.) R. Br.; *Capsella bursa-pastoris* (L.) Medik.; *Chenopodium album* L.; *Chorispora tenella* (Pall.) DC.; *Cirsium segetum* Bunge; *Cirsium setosum* (Willd.) Bieb.; *Convolvulus arvensis* L.; *Conyza canadensis* (L.) Cronquist; *Descurainia sophia* (L.) Webb ex Prantl; *Equisetum ramosissimum* Desf.; *Erigeron annuus* (L.) Pers.; *Erysimum cheiranthoides* L.; *Euphorbia helioscopia* L.; *Galium aparine* L.; *Geranium carolinianum* L.; *Hemistepta lyrata* (Bunge) Bunge; *Hibiscus syriacus* L.; *Hordeum vulgare* L.; *Humulus japonicus* Siebold & Zucc.; *H. scandens* (Lour.) Merr.; *Lithospermum arvense* L.; *Mazus pumilus* (Burm.f.) Steenis; *Phragmites communis* Trin.; *Plantago major* L.; *Plantago virginica* L.; *Polygonum*	Menegat et al. (2013), Han et al. (2014), Tang et al. (2013), Yin et al. (2005), Lu et al. (2012)

(continued)

Table 20.3 (continued)

Country/ region	Important weed flora	References
	amphibium L.; *Polygonum aviculare* L.; *Silene conoidea* L.; *Stellaria media* (L.) Vill.; *Veronica persica* Poir.; *Vicia cracca* L.; *Vicia sativa* L.	
Czech-Republic	*Elytrigia repens* (L.) Nevski; *Galium aparine* L.; *Lamium amplexicaule* L.; *Papaver rhoeas* L.; *Tripleurospermum inodorum* (L.) Sch. Bip.; *Viola arvensis* Murray;	Hamouz et al. (2013)
Denmark	*Avena sativa* L.; *Brassica napus* L.; *Capsella bursa-pastoris* (L.) Medik.; *Chenopodium album* L.; *Lamium* spp.; *Lolium multiflorum* Lam.; *Matricaria perforata* Merat; *Papaver rhoeas* L.; *Polygonum persicaria* L.; *Sinapis alba* L.; *Sinapis arvensis* L.; *Stellaria media* (L.) Vill.;	Rasmussen (2004), Melander et al. (2003), Olsen et al. (2006, 2012)
Egypt	*Ammi majus* L.; *Avena fatua* L.; *Centaurea calcitrapa* L.; *Chenopodium album* L.; *Coronopus squamatus* (Forssk.) Asch.; *Lolium multiflorum* Lam.; *Melilotus indica* (L.)	Kowthar et al. (2012)
Ethiopia	*Avena fatua* L.; *Bromus pectinatus* Thunb.; *Caylusea abyssinica* (Fresen.); *Caylusea trigyna* L.; *Chenopodium album* L.; *Corrigiola capensis* Willd.; *Guizotia scabra* (Vis.) Chiov.; *Oxalis latifolia* Kunth.; *Phalaris paradoxa* L.; *Polygonum nepalense* Meisn.; *Raphanus raphanistrum* L.; *Spergula arvensis* L.; *Tagetes minuta* L.	Taa et al. (2004), Amare et al. (2014), Kebede (2017), Addisu (2019)
France	*Fallopia convolvulus* L.; *Polygonum aviculare* L.; *Veronica hederifolia* L.; *Veronica persica* Poir	Gaba et al. (2010)
Germany	*Alopecurus myosuroides* Huds.; *Capsella bursa-pastoris* (L.) Medik.; *Centaurea cyanus* L.; *Cerastium glomeratum* Thuill.; *Cirsium arvense* (L.) Scop.; *Galium aparine* L.; *Lamium amplexicaule* L.; *Lamium purpureum* L.; *Matricaria chamomilla* L.; *Matricaria recutita* L.; *Myosotis arvensis* (L.) Hill; *Papaver rhoeas* L.; *Poa annua* L.; *Stellaria media* (L.) Vill.; *Veronica hederifolia* L.; *Veronica persica* Poir.; *Viola arvensis* Murray	Gerhards et al. (2002), Ulber et al. (2010), Keller et al. (2014)

(continued)

Table 20.3 (continued)

Country/ region	Important weed flora	References
Greece	*Avena sterilis* L.; *Papaver rhoeas* L.; *Phalaris minor* Retz.; *Sinapis arvensis* L	Travlos (2012)
Hungary	*Bilderdykia convolvulus* (L.) Dumort; *Cannabis sativa* L.; *Chenopodium album* L.; *Chenopodium hybridum* L.; *Cirsium arvense* (L.) Scop.; *Papaver rhoeas* L.; *Sisymbrium sophia* L.	Reisinger et al. (2005)
India	*Anagallis arvensis* L.; *Argemone mexicana* L.; *Avena fatua* L.; *Avena ludoviciana* Dur.; *Asphodelus tenuifolius* Cav.; *Chenopodium album* L.; *Chenopodium murale* L.; *Convolvulus arvensis* L.; *Coronopus didymus* L.; *Cirsium arvense* L; *Daucus carota* L.; *Euphorbia helioscopia* L.; *Fumaria parvi flora* Lamk.; *Lathyrus aphaca* L.; *Malva parviflora*; *Medicago denticulata* Willd; *Melilotus alba* Lamk.; *Melilotus indica* All.; *Phalaris minor* Retz.; *Poa annua* L.; *Polygonum plebeium* R. Br.; *Polypogon monsplensis* (L.) Desf.; *Rumex dentatus* L.; *Solanum nigrum*; *Spergula arvensis* L.; *Stellaria media* (L.) Vallars; *Trigonella incisa* Benth.; *Trigonella polycerata*; *Veronica agrestis* L.; *Vicia sativa* L.; *Vicia hirsuta* Koch.	Singh et al. (1995b), Chhokar et al. (2012)
Iran	*Alyssum hirsutum* M. Bieb.; *Anthemis cotula* L.; *Arenaria lateriflora* L.; *Avena fatua* L.; *Beta maritima* L.; *Bromus* spp.; *Carduus pycnocephalus* L.; *Carthamus tinctorius* L.; *Centaurea depressa* M. Bieb.; *Consolida orientalis* (J. Gay) Schrodinger; *Descurainia sophia* (L.) Webb ex Prantl; *Erysimum crassicaule* (Boiss.) Boiss.; *Galium tricornutum* Dandy; *Galium tricorne* Stokes; *Hordeum* spp.; *Lamium amplexicaule* L.; *Lepyrodiclis holosteoides*; *Lolium perenne* L.; *Lolium rigidum* Gaudin; *Malcolmia africana* L.; *Malva neglecta*; *Malva sylvestris* L.; *Melilotus officinalis* (L.) Pall.; *Phalaris minor* Retz.; *Polygonum aviculare* L.; *Polygonum convolvulus* L.; *Scandix*	Zand et al. (2007a,b), Zand et al. (2010), Vazan et al. (2011), Behdarvand et al. (2013)

(continued)

Table 20.3 (continued)

Country/ region	Important weed flora	References
	pecten-veneris L.; *Silybum marianum* (L.) Gaertn.; *Sinapisarvensis* L.; *Vaccaria pyramidata* Medik; *Veronica persica* Poir.	
Japan	*Alopecurus aequalis* Sobol.; *Beckmannia syzigachne*; *Camelina microcarpa* Andrz. ex DC; *Centaurea cyanus* L.; *Cerastium glomeratum* Thuill.; *Descurainia sophia* (L.) Webb ex Prantl; *Galium spurium* L.	Samarajeewa et al. (2005), Sekiguchi et al. (2013)
Jordan	*Adonis annua*; *Adonis dentate*; *Aegilops umbellulata* Zhuk; *Avena sterilis* L.; *Bromus tectorum* L; *Bongardia chrysoganum* (L.) Boiss; *Cyanodon dactylon* (L.) Pers.; *Diplotaxis erucoides* (L.) DC.; *Sinapis alba*L; *Phalaris brachystachys* Link; *Phalaris paradoxa*L.; *Stellaria media* L.	Turk and Tawaha (2003)
Lebanon	*Cardaria draba* (L.) Desv.; *Convolvulus arvensis* L.; *Leontice leontopetalum* L.	Saghir (1977)
Middle East	*Anthemis cotula* L.; *Capsella bursa-pastoris* (L.) Medic.; *Carthamus oxyacanthus* M.B.; *Cephalaria syriaca (L.)* Schrad.; *Cirsium acarna* (L.) Moench.; *Polygonom aviculare L. Raphanus raphanistrum L., Sinapis arvensis L.*	Saghir (1977)
Nepal	*A. aequalis*, *A. fatua*; *Cannabis sativa* L.; *C. album*; *P. minor*; *P. hydropiper*; *Polypogon fugax*;*Vicia* spp.; *P. plebeium*; *S. anthemifolia*; *Stellaria uliginosa*	Chaudhary and Shrestha (1981), Joshi (1996)
Nigeria	*Chenopodium album* L.; *Convolvulus arvensis* L.; *Cyperus rotundus* L.; *Fumaria parviflora* Lam.; *Lathyrus aphaca* L.	Dadari and Mani (2005)
Pakistan	*Anagallis arvensis* L.; *Avena fatua* L.; *Chenopodium album* L.; *C. murale* L.; *Cirsium arvense* L.; *Convolvulus arvensis* L.; *Coronopus didymus* L.; *Cynodon dactylon* L.; *Cyperus rotundus* L.; *Euphorbia helioscopia* L.; *Fumaria indica* (Hausskn.) Pugsley; *Fumaria parviflora* Lam.; *Malva parviflora* L.; *Medicago denticulata* Willd.; *Melilotus indica* (L.) All.;	Khan and Marwat (2006), Usman et al. (2010), Jabran et al. (2012), Mahmood et al. (2012), Mahmood et al. (2012), Hussain et al. (2013), Tang et al. (2014)

(continued)

Table 20.3 (continued)

Country/ region	Important weed flora	References
	Phalaris minor Retz.; *Poa annua* L.; *Rumex dentatus* L.; *Silybum marianum* (L.) Gaertn.; *Solanum nigrum* L.; *Vicia sativa* L.	
Poland	*Anchusa arvensis* L.; *Apera spica-venti* (L.) P. Beauv.; *Artemisia vulgaris* L.; *Bromus secalinus* L.; *Capsella bursa-pastoris* (L.) Medik.; *Centaurea cyanus* L.; *Chamaemelum mixtum* (L.) All.; *Chenopodium album* L.; *Cirsium arvense* (L.) Scop.; *Conyza canadensis* (L.) Cronquist; *Elymus repens* (L.) Gould; *Equisetum arvense* L.; *Fallopia convolvulus* L.; *Galeopsis tetrahit* L.; *Galinsoga parviflora* Cav.; *Gnaphalium uliginosum* L.; *Juncus bufonius* L.; *Lamium amplexicaule* L.; *Lycopsis arvensis* L.; *Matricaria maritima* L.; *Plantago intermedia* Gilib.; *Plantago major* L.; *Poa annua* L.; *Polygonum aviculare* L.; *Rumex crispus* L.; *Senecio vulgaris* L.; *Setaria pumila* (Poir.) Roem. & Schult; *Setaria viridis* (L.) P._Beauv.; *Sonchus arvensis* L.; *Sonchus asper* (L.) Hill; *Stellaria media* (L.) Vill.; *Taraxacum officinale* (L.) Weber; *Trifolium pratense* L.; *Trifolium repens* L.; *Veronica arvensis* L.; *Veronica persica* Poir.; *Vicia tetrasperma* (L.) Schreb.; *Viola arvensis* Murray;	Barros et al. (2009), Harasim et al. (2014), Pawlonka and Rymuza (2014)
Portugal	*Anagallis arvensis* L.; *Calendula arvensis* M. Bieb.; *Chamaemelum mixtum* (L.) All.; *Chrysanthemum segetum* L.; *Daucus carota* L.; *Echium plantagineum* L.; *Galium aparine* L.; *Lactuca serriola* L.; *Lamium amplexicaule* L.; *Lolium rigidum* Gaudin; *Plantago afra* L.; *Polygonum aviculare* L.; *Scandix pecten-veneris* L.; *Silene nocturna* L.; *Torilis arvensis* (Huds.) Link	Barros et al. (2009, 2016)
Russia	*A. fatua*, *Alopecurus* spp., *C. album*; *Convolvulus arevensis*; *Galium aparine*; *Descurainia Sophia*; *F. convolvulus*; *Sonchus arevensis*; *S. viridis*	Kraehmer (2016)
Romania	*Amaranthus retroflexus*; *Avena fatua*; *Bromus sterilis*; *Capsella bursa-*	Torcea and Cârciu (2018)

(continued)

Table 20.3 (continued)

Country/ region	Important weed flora	References
	pastoris; *Chenopodium album*; *Convolvulus arevensis*; *Cirsium arvense*; *Veronica persica*; *Delphynium consolida*; *Stellaria media*; *Centaurea cyanus*; *Matricaria inodora*	
Spain	*Anacyclus clavatus (*Desf.) Pers.; *Avena sterilis* L.; *Buglossoides arvensis* (L.) I.M. Johnstn.; *Capsella bursa-pastoris* (L.) Medik.; *Cardaria draba* (L.) Desv.; *Cirsium arvense* (L.) Scop.; *Convolvulus arvensis* L.; *Descurainia sophia* (L.) Webb ex Prantl; *Echium plantagineum* L.; *Fumaria officinalis* L.; *Hypecoum imberbe* Sm.; *Lamium amplexicaule* L.; *Papaver rhoeas* L.; *Phalaris brachystachys* Link; *Silene vulgaris* (Moench) Garcke; *Veronica hederifolia* L.	Ponce and Santin (2001), Jurado-Expósito et al. (2005), Gonzalez-Andujar et al. (2005), Santın-Montanyá et al. (2013)
Turkey	*Adonis aestivalis* L.; *Alopecurus myosuroides* Huds.; *Avena* spp.; *Cephalaria sparsipilosa* V.A. Matthews; *Descurainia sophia* (L.) Webb ex Prantl; *Galium aparine* L.; *Lactuca serriola* L.; *Polygonum bellardii* All.	Mennan and Işik (2004), Mennan and Zandstra (2005), Ozturk et al. (2012)
United Kingdom	*Alopecurus myosuroides* Huds; *Galium aparine* L.; *Lamium* spp.; *Matricaria* spp.; *Poa annua* L.; *Stellaria media* (L.) Vill.; *Veronica* spp.	Blair et al. (2002), Korres and Froud-Williams (2002)
USA	*Aegilops cylindrica* Host, *Amsinckia* spp., *Avena fatua* L., *Bromus secalinus* L.; *Bromus tectorum* L.; *Chenopodium album* L.; *Chenopodium pallescens* Standl.; *Chondrilla juncea* L.; *Cirsium arvense* (L.) Scop*.; Conyza canadensis* (L.) Cronquist; *Descurainia sophia* (L.) Webb ex Prantl; *Epilobium brachycarpum* C. Presl; *Galeopsis tetrahit* L.; *Galium aparine* L.; *Gnaphalium* sp.; *Lactuca serriola* L.; *Lamium amplexicaule* L.; *Lolium multiflorum* Lam.; *Lolium perenne* L.; *Polygonum lapathifolium* L.; *Salsola tragus* L.; *Sinapis alba* L.; *Sisymbrium altissimum* L.; *Tragopogon* spp.	Sullivan et al. (2013), Conley and Bradley (2005), Girma et al. (2005), DeBoer et al. (2006), Kolb et al. (2012), Worthington et al. (2013)

Table 20.4 Comparative differences in wheat associated grass weeds

Character	*Phalaris minor*	*Avena ludoviciana*	*Polypogon monspeliensis*	*Lolium perenne*	*Poa annua*
Common name	Little seed canary grass	Wild oat	Rabitt foot grass/fox tail grass	Perennial rye grass	Annual meadow grass
Local Indian name	Gulli danda/Kanki/mandusi	Jangli javi	Loombar ghas	Rye grass	Bueen/Poa ghass
Family	Gramineae	Gramineae	Gramineae	Gramineae	Gramineae
Origin	Mediterranean	Mediterranean	Southern Europe	Mediterranean	Europe
Ontogeny	Annual	Annual	Annual	Perennial	Annual
Germination	November to January and matures in March–April	October–November and matures in March–April	November–December and matures in March–April	November and matures in April	November–December and matures in March–April
Optimum temperature for growth	10–20 °C	20–25 °C	10–20 °C	15–20 °C	20 °C
Plant height (cm)	100–130 cm and 10–20 cm more height than wheat	100–120 cm and taller than wheat	10–100 cm and less than that of wheat	30–48 cm	15–30 cm
Leaf	Light pale green, linear smooth with purplish green spots at the junction of lamina and leaf, pink colour exudates come out on crushing.	Long broad leaves, bright green, no serration and hairs are present at the margins, leaves linear with broad base and acute apex, 7–20 cm long and 5–15 mm twisted counter-clockwise	At seedling stage leaf blades are very slender with hair like greenish yellow in colour, Linear soft and Light green, leaf blade 5–20 cm length and 0.6 mm in width	Hairless narrow leaves having parallel veins on the upper surface, dark green, about 6 mm wide, Leaves are folded lengthwise in bud.	Smooth, soft, linear. Length 7 cm and width 1–5 mm. light green with a prow and boat shaped tip
Stem	Solid, erect, branched, pink or purple at the base up to 50 days of	Hollow, unbranched, thick and tight	Erect or prostrate, very thin	Nodes and internodes are present in flowering stems, peduncle is the	At seedling stage sheath and blade are glabrous weak

(continued)

Table 20.4 (continued)

Character	*Phalaris minor*	*Avena ludoviciana*	*Polypogon monspeliensis*	*Lolium perenne*	*Poa annua*
	growth, root-shoot ratio is about 1: 9, internode pinkish in colour			uppermost culm segment support the flowering parts	
Tillering	Rossete type, both tillering and branching, 2–3 tillering from single seed	Tillering	Tillering	Tillering, bunchgrass type growth habit	Profuse tillering with fibrous root system
Ligule	Ligule is prominent approx. Three times to that of wheat (0.5–1.0 cm long clasp the stem)	Prominent broad serrated and membranous	Ligule erectile membrane 3–15 mm long, Cone shaped, light serration at tip	Poorly developed, very short and squared off	ligules thinly membranous and silvery 2–5 mm long
Auricle	Absent, hairs present at junction of leaf sheath and lamina	Absent, no hairs at the junction of leaf sheath and lamina	absent	Poorly developed	absent
Inflorescence	2.0–10 cm long dense oblong and ovate panicle	Panicle is loose and open,15–30 cm long and 7–20 cm wide, many green spikelets and each spikelets have 2–3 brownish green florets	Panicles are light greenish, silky and dense Terminal, very soft, 2-16 cm in length, 1–35 cm wide with yellowish white in colour	Terminal, spikelets 8–12 mm long typically have 8–11 florets Spikelets alternating up to the axis	Terminal, pyramidal flower head loose with greenish purple in colour, spikelets small, 3–6 florets and lemma is awnless
Seed production	400–600 seed per ear head and approx. 10,000–30,000 seed per plant, viability upto 6 years	Propagation by seeds only, 200–400 seed/ plant	Propagation is through small, amber coloured seeds, 75,000 seed per plant	45,000 seeds per meter^2	1000–2500 seeds per plant Propagation through caryopsis small seeds,

Seed morphology	Glumes 4.0–6.0 mm long; fertile lemma 3.5–4.0 mm, 1.5 mm wide; Dark brown; oval in shape; smooth and shinning	Seeds are 11.0–14 mm long; 2.0–5.5 mm wide; floret elongated, narrow and broadest near base; long black awn originates at about middle of lemma. Floret colour is usually grey brownish or black,	Seed sky blue in colour very tiny	Always lack awns, whereas *L. multiflorum* nearly always has awns.	Small, flattened, pointed at both the ends and bright amber in colour
Growth pattern	Erect	Erect	Spreading and erect	Erect	Spreading in nature
Special features	Irrigated condition, more in rice wheat cropping system, evolved multiple herbicide resistance to different herbicides	More in well drained light textured soils; loose viability with stagnant water so poor infestation in wheat in rice wheat cropping system, Differ from cultivated oat as presence of long silky hairs around its base	Tufted grass more in moist and fertile soil condition and along the bunds and channels, more in late sown conditions.	Also utilized as a turf grass species and pasture or hay	Moist condition/ irrigated field Shows a mat like appearance in field. Mostly present in late sown wheat, sweetest grass for green fodder

Source: Naidu 2012; Susheela and Sathyanarayana 2021 increased with increase in burial depth (10 and 20 cm) as compared to seeds in the upper soil layers of <5 cm. After 360 days of burial, greater burial depth (10 and 20 cm) exhibited 10% lower deteriorated seeds as compared to 0.5 cm burial. More than 95% of seeds loss viability at 540 days after burial indicating short persistence of soil seed bank of ryegrass. Dormancy breakage occurred more quickly at 10 and 20 cm depths, but until 180 days after burial (Cechin et al. 2020). Moreover, under current climatic scenario, the seed bank of *Lolium multiflorum* L. grew with equilibrium density of 20,463 ± 363 and 19,121 ± 371 seeds m^{-2}, respectively for the resistant and susceptible populations. While, an increase of 2.5 °C in average air temperature, the seed bank intensified with equilibrium density of 24,299 ± 254 seeds m^{-2} (+18% compared to existing conditions) and 24,182 ± 253 seeds m^{-2} (+26% compared to existing conditions) for the resistant and susceptible, respectively (Pagnoncelli et al. 2020). This indicates Italian ryegrass population is likely to be increased in all management strategies in future and may halt sustainable wheat production. Weed community was greatly influenced by regions and cultivation methods (Scursoni et al. 2014).

Black-grass (*Alopecurus myosuroides*) is an annual problematic grass-weed reproducing solely by seeds and favored by water retentive soils such as heavier clay or silt loam compared to lighter sandy soils. Early autumn seedling emergence, emergence from shallow depth (<5 cm), small longevity (< 5 years), more population growth (>ten-fold increase in a single year) are the important agro-ecological factors contributes in its infestation. Further, Moss (2017) summarized practices that favor its proliferation in Western Europe as: 1) The trend of growing more autumn sown crops and earlier has increased and the same resulted in high proportion of black-grass plants emerging with the crop rather than before sowing, 2) Accelerated increase in the use of non-inversion cultivations (minimum/shallower tillage or no till) since, 2000 that retains most freshly shed seeds in upper soil profile (< 5 cm) and subsequently recruits seedlings and 3) sole dependence on herbicides that makes this weed to combat action of multiple herbicides. So, to tackle this situation '5 for 5' initiative is laid out to adopt comprehensive strategies for reducing black-grass infestation in a planned, integrated approach at the individual field level for at least five years (Moss 2017; Lutman et al. 2013). Lutman et al. (2013) reviewed potential of non-chemical approaches in reducing *Alopecurus myosuroides*, and observed that delaying autumn sowing, increased seeding rate, competitive crop cultivars and spring cropping can reduce the infestation by 31, 26, 22 and 88%, respectively.

A. sterilis ssp. ludoviciana is recognized as hard to control winter grass weed in Australia especially following the large scale adoption of no-till in CA. Different survival mechanisms such as variable seed dormancy, early shedding of highly germinable seeds, are involved in its survival and persistence in no-till conditions (Ali et al. 2019). At seed development stage, soil water stress resulted in 16–22% less seed with 28% less dormant but 5–20 days earlier as compared to control. This has a practical implication, as frequent dry and hot period during the seed development in northern Australia is likely to produce less dormant seeds and no-till system retaining these less dormant seeds on the top surface soil and this may favour re-infestation in the autumn/winter-sown wheat crop, once the favorable germination conditions reformed (Ali et al. 2019).

Avena fatua (L.) is an important grass weed in wheat and barley crops infesting 60% of the fields of an area of 750,000 ha of Argentina. In the USA, it infests more than 11 m ha and accounting economical loss of trillion dollars (Evans et al. 1991). Also, in China, it invades over 5 m ha causing annul loss of 1.75 mt grain (Li et al. 2007). Similarly, this weed cause serious reduction in grain yield of winter cereals in Australia, Spain, India and United Kingdom etc. Martín and Scursoni (2018) studied emergence dynamic of *Avena fatua* from two different origins (agricultural fields and without cropping conditions) and observed seeds from cultivated areas have shown higher dormancy and late emergence than those from no cropped areas. The variable dormancy nature and subsequent germination dynamics of *Avena fatua* on the field was hierarchically more imperative than herbicidal responses to favor its persistence in wheat based systems.

Another problematic grass weed in more than 60 countries is *Phalaris minor* (Singh et al. 1999). Under field conditions, dormancy of *P. minor* seeds was recorded about 60 days (Om et al. 2004, 2005) as after wheat harvesting it showed more germination (80–96%) with viability of seed was only for the maximum ten months (or forthcoming season). At room temperature stored 65 month old seeds exhibited 72% germination that reduced to 0% in 101 months (Chhokar 1998). However, loss in germinability/seed longevity of *P. minor* seeds is considerably affected by soil texture, soil aeration, moisture, temperature, and seeding depth. The buried seed in sandy loam aerobic soil under fallow-wheat rotation has completely lost germinability, while in soil characterized by anaerobic soil environment due to puddled conditions in rice with more clay content still germinated (Franke et al. 2007) as half-life of buried seeds was 15 months in heavy texture, seasonal anaerobic and poorly aerated soil as compared to 10 months in light textured soil. However, buried seed of *P. minor* completely lost the ability to germinate after two years (Franke et al. 2007) and lab stored seed loss viability after 6 years. The restricted seed viability and short longevity providing opportunities to diversify rotation of puddle transplanted rice-wheat rotation to reduce its infestation significantly. Even one year break from continuous wheat or rice-wheat rotation could be devised to reduce *P. minor* seed bank. A study on comparative behavior of *P. minor* and *P. brachystachys* under-five levels of water availability showed significant differences as field capacity and light drought regimes favored more biomass, tillers, and panicle density in *P. minor*. On the other hand, *P. brachystachys* (2n = 12) showed positive response in moderate drought regime and mature panicle percentage increased with the increased drought levels. The findings indicated comparatively greater distribution of *P. minor* in irrigated fields, whereas, *P. brachystachys* (short-spiked canary grass) in semi-arid areas because of its moderate drought adaptation (Braña et al. 2010).

Rumex dentatus is an important broad-leaved weed associated with wheat under rice-wheat system in India. Its germination significantly increases at 15, 18/8 and 21/10 °C as compared to nil at constant temperatures of 35 and 45 °C and even at alternating temperature 36/10 °C and 28/14 °C. However, more germination was recorded with temperature as 18/8 °C. The imbibed seeds of *R. dentatus* contain an abundant reserve of starch that constitutes about 21% of the seeds fresh weight (Al-Helal 1996). The *R. dentatus* seeds survives under flooded conditions in paddy and due to lighter in weight during puddling float on the surface and accumulates and emerge in greater number when succeeding wheat is shown under zero till conditions. Therefore, flooding may not help in lowering *R. dentatus* emergence but deep tillage has tendency to bury the seed to greater depth (>4 cm), where seeds failed to emergence and resulted in lower infestation in next season wheat crop (Singh and Punia 2008). *R. dentatus* emergence was similar from 0 to 1 cm depths of about 61–70% but significantly reduced at 2 cm depth (33%) and only 3% seed emerged beyond 4 cm and thereafter (>8 cm) no emergence was recorded (Singh and Punia 2008). This could be the reason for its greater propensity under ZT as most of the seed lies on surface with maximum potential of germination as compared to burying in CT. The *P. minor* germination increased under red light but not *Medicago hispida,* while, green light favored more germination of *Avena ludoviciana* (Mishra et al. 2005). Among two factors i.e. altering temperature and light, former was reported as most important for seed germination in *Avena fatua*, *Bromus catharticus*, *Chenopodium album* and *P. minor*.

20.5 Herbicide Resistance Issues Associated with Wheat and Barley Weeds

Escalating evolution of herbicide-resistant weed populations is becoming a threat for global food grain production. Herbicide based crop production systems have aggravated the proliferation of herbicide resistant biotypes (Table 20.5) in most of the commonly found weed species (Walsh et al. 2012). The herbicide resistance development in weeds is an evolutionary but dynamic phenomenon and depends on numerous factors i.e., biology, ecology and genetics of weeds; herbicidal application (method, dose, time) and other biological components (Beckie 2006; Singh 2007: Chhokar et al. 2018). Herbicide resistance development in weed occurs by one of two principal mechanisms that lead to different pattern of resistance. The most common mechanism (target site resistance) in which target site point mutation (s) results in development resistance. While, other one is based on enhanced metabolism (non-target site resistance) in which herbicide molecules resulted in non-toxic or less phytotoxic molecules and generally leads low level of resistance (Yu and Powles 2014; Duke 2012). *Lolium rigidum* Gaud (annual ryegrass) in cereal crops of southern Australia has developed resistance to both group A and group B herbicides and now herbicide-resistant biotypes are more frequent in Australian fields (Boutsalis et al. 2012). ACCase-inhibiting aryloxyphenoxypropionate and cyclohexanedione, and ALS-inhibiting resistances in southern Australia in annual ryegrass are more in wheat based cropping system and predominantly in acidic soils (Broster et al. 2019). There is need to strengthen the principles of rotating herbicides of different modes of action with cultural based weed control measures to minimize the herbicide resistance evolution risk.

Table 20.5 Major herbicide resistant weeds associated with wheat against different mode of action in major wheat producer countries (Heap 2020; Chhokar et al. 2018)

Country	Weed species	Mode of Action (Based on site of inhibition)
Argentina	*Avena fatua*	ACCase (A/1)
	Brassica rapa (=B. campestris)	ALS (B/2), EPSP synthase (G/9), Synthetic Auxins (O/4)
	Bromus catharticus	EPSP synthase (G/9)
	Hirschfeldia incana	ALS (B/2), Synthetic Auxins (O/4)
	Lolium perenne	EPSP synthase (G/9)
	Lolium perenne ssp. multiflorum	ALS (B/2), EPSP synthase (G/9)
	Raphanus sativus	ALS (B/2)
Australia	*Avena fatua*	ACCase (A/1), ALS (B/2), Anti-microtubule mitotic disrupter (Z/25)
	Avena sterilis	ACCase (A/1)
	A. sterilis ssp. ludoviciana	Anti-microtubule mitotic disrupter (Z/25), ACCase (A/1), ALS (B/2)
	Brassica tournefortii	ALS (B/2)
	Bromus diandrus	ALS (B/2), EPSP synthase (G/9)
	Bromus rigidus	ALS (B/2)
	Conyza sumatrensis	PSI (electron diverter) (D/22)
	Galium tricornutum	ALS (B/2)
	Hordeum murinum ssp. glaucum	ALS (B/2)
	Lactuca serriola	ALS (B/2)
	Lolium rigidum	ACCase (A/1), ALS (B/2), EPSP synthase (G/9), Lipid (N/8), DOXP (F4/13), Long chain fatty acid (K3/15), Microtubule (K1/3), Mitosis (K2/23)
	Mesembryanthemum crystallinum	ALS (B/2)
	Phalaris minor	ACCase (A/1)
	Phalaris paradoxa	ACCase (A/1), ALS (B/2)
	Polygonum convolvulus	ALS (B/2)
	Raphanus raphanistrum	Synthetic Auxins (O/4), ALS (B/2)
	Rapistrum rugosum	ALS (B/2)
	Sinapis arvensis	ALS (B/2)
	Sisymbrium orientale	ALS (B/2)
	Sisymbrium thellungii	ALS (B/2)
	Sonchus oleraceus	ALS (B/2), Synthetic Auxins (O/4)
	Urochloa panicoides	EPSP synthase (G/9)
Belgium	*Alopecurus myosuroides*	PSII (Ureas and amides) (C2/7)
	Apera spica-venti	ALS (B/2)
	Avena fatua	ACCase (A/1)

(continued)

Table 20.5 (continued)

Country	Weed species	Mode of Action (Based on site of inhibition)
	Matricaria recutita (= M. chamomilla)	ALS (B/2)
	Papaver rhoeas	ALS (B/2)
	Stellaria media	ALS (B/2)
Bolivia	*Eleusine indica*	ACCase (A/1)
Brazil	*Conyza bonariensis*	EPSP synthase (G/9)
	Echium plantagineum	ALS (B/2)
	Eleusine indica	EPSP synthase (G/9)
	Lolium perenne ssp. Multiflorum	ALS (B/2), ACCase (A/1), EPSP synthase (G/9)
	Raphanus raphanistrum	ALS (B/2)
	Raphanus sativus	ALS (B/2)
Canada	*Amaranthus powellii*	ALS (B/2), Photosystem II (C1/5)
	Amaranthus retroflexus	ALS (B/2)
	Avena fatua	ACCase (A/1), ALS (B/2), Lipid (N/8), Anti microtubule mitotic disrupter (Z/25)
	Capsella bursa-pastoris	ALS (B/2)
	Chenopodium album	ALS (B/2)
	Galeopsis tetrahit	Synthetic Auxins (O/4), ALS (B/2)
	Galium spurium	ALS (B/2), Synthetic Auxins (O/4)
	Kochia scoparia	ALS (B/2), EPSP synthase (G/9), Synthetic Auxins (O/4)
	Lolium persicum	ACCase (A/1)
	Neslia paniculata	ALS (B/2)
	Polygonum convolvulus	ALS (B/2)
	Polygonum lapathifolium	ALS (B/2)
	Salsola tragus	ALS (B/2)
	Setaria viridis	Microtubule (K1/3), ACCase (A/1), ALS (B/2)
	Sinapis arvensis	Synthetic Auxins (O/4), ALS (B/2), Photosystem II (C1/5)
	Sonchus asper	ALS (B/2)
	Stellaria media	ALS (B/2)
	Thlaspi arvense	ALS (B/2)
	Vaccaria hispanica	ALS (B/2)
Chile	*Anthemis arvensis*	ALS (B/2)
	Anthemis cotula	ALS (B/2)
	Avena fatua	ACCase (A/1)
	Cynosurus echinatus	ACCase (A/1), ALS (B/2)

(continued)

Table 20.5 (continued)

Country	Weed species	Mode of Action (Based on site of inhibition)
	Lolium perenne ssp. multiflorum	ACCase (A/1), ALS (B/2), EPSP synthase (G/9)
	Lolium rigidum	ACCase (A/1), ALS (B/2)
	Raphanus sativus	ALS (B/2)
	Silene gallica	ALS (B/2)
China	*Alopecurus aequalis*	ACCase (A/1), ALS (B/2)
	Alopecurus japonicus	PSII (Ureas and amides) (C2/7), ACCase (A/1), ALS (B/2)
	Beckmannia syzigachne	PSII (Ureas and amides) (C2/7)
	Buglossoides arvensis	ALS (B/2)
	Capsella bursa-pastoris	ALS (B/2)
	Descurainia sophia	Synthetic Auxins (O/4)
	Galium aparine	Synthetic Auxins (O/4)
	Myosoton aquaticum	ALS (B/2)
	Polypogon fugax	ACCase (A/1)
	Rorippa indica	ALS (B/2)
	Sclerochloa kengiana	ACCase (A/1)
	Stellaria media	Synthetic Auxins (O/4)
	Vicia sativa	ALS (B/2)
Czech Republic	*Alopecurus myosuroides*	ALS (B/2)
	Apera spica-venti	ALS (B/2) PSII (Ureas and amides) (C2/7)
	Bromus sterilis	ALS (B/2)
Denmark	*Alopecurus myosuroides*	ACCase (A/1)
	Apera spica-venti	ACCase (A/1), ALS (B/2)
	Capsella bursa-pastoris	ALS (B/2)
	Lolium perenne	ACCase (A/1), ALS (B/2)
	Lolium perenne ssp. Multiflorum	ACCase (A/1), ALS (B/2)
	Papaver rhoeas	ALS (B/2)
	Stellaria media	ALS (B/2)
	Tripleurospermum perforatum	ALS (B/2)
Ethiopia	*Snowdenia polystachya*	ACCase (A/1)
Finland	*Chenopodium album*	ALS (B/2)
France	*Alopecurus myosuroides*	ACCase (A/1), ALS (B/2)

(continued)

Table 20.5 (continued)

Country	Weed species	Mode of Action (Based on site of inhibition)
	Apera spica-venti	ALS (B/2)
	Avena fatua	ACCase (A/1), ALS (B/2)
	Avena sterilis	ALS (B/2)
	A. sterilis ssp. ludoviciana	ACCase (A/1)
	Bromus sterilis	ALS (B/2)
	Lolium perenne ssp. multiflorum	ACCase (A/1), ALS (B/2), Long chain fatty acid (K3/15)
	Lolium rigidum	ACCase (A/1), ALS (B/2)
	Papaver rhoeas	ALS (B/2), Synthetic Auxins (O/4)
	Poa annua	ALS (B/2)
	Poa trivialis	ALS (B/2)
	Rumex obtusifolius	ALS (B/2)
	Senecio vulgaris	ALS (B/2)
	Stellaria media	ALS (B/2)
	Tripleurospermum perforatum	ALS (B/2)
Germany	*Alopecurus myosuroides*	ACCase (A/1), PSII (Ureas and amides) (C2/7), ALS (B/2), Long chain fatty acid (K3/15),
	Apera spica-venti	ALS (B/2)
	Bromus sterilis	ALS (B/2)
	Lolium perenne	ACCase (A/1), ALS (B/2)
	Matricaria recutita	ALS (B/2)
	Stellaria media	ALS (B/2)
	Tripleurospermum perforatum	ALS (B/2)
Finland	*Stellaria media*	ALS (B/2)
Greece	*Avena sterilis*	ACCase (A/1)
	Lolium rigidum	ACCase (A/1), ALS (B/2)
	Papaver rhoeas	ALS (B/2), Synthetic Auxins (O/4)
India	*Phalaris minor*	PSII (Ureas and amides) (C2/7), ACCase inhibitors (A/1), ALS (B/2)
	**Rumex dentatus*	ALS (B/2)
	**Avena ludoviciana*	ACCase (A/1)
	**Chenopodium album*	ALS (B/2)
	**Polypogon monspeliensis*	ALS (B/2)
Iran	*Avena fatua*	ACCase (A/1)
	Avena sterilis	ACCase (A/1), ALS (B/2)
	Avena sterilis ssp. Ludoviciana	ALS (B/2)
	Lolium rigidum	ACCase (A/1)
	Galium aparine	Synthetic Auxins (O/4), ALS (B/2)

(continued)

Table 20.5 (continued)

Country	Weed species	Mode of Action (Based on site of inhibition)
	Phalaris brachystachys	ACCase (A/1)
	Phalaris minor	ACCase (A/1)
	Phalaris paradoxa	ACCase (A/1)
	Rapistrum rugosum	ALS (B/2)
	Sinapis arvensis	ALS (B/2)
Ireland	*Avena fatua*	ACCase (A/1)
Israel	*Avena sterilis*	ACCase (A/1)
	Chrysanthemum coronarium	ALS (B/2)
	Diplotaxis erucoides	ALS (B/2)
	Erucaria hispanica	ALS (B/2)
	Lolium rigidum	ACCase (A/1), ALS (B/2), EPSP synthase (G/9)
	Phalaris minor	ACCase (A/1)
	Phalaris paradoxa	ACCase (A/1)
	Senecio vernalis	ALS (B/2), Carotenoid biosynthesis (F1/12), Photosystem II (C1/5), PPO (E/14), PSII (Ureas and amides) (C2/7)
Italy	*Avena sterilis*	ACCase (A/1)
	Lolium perenne ssp. multiflorum	ACCase (A/1), EPSP synthase (G/9), ALS (B/2),
	Papaver rhoeas	ALS (B/2), Synthetic Auxins (O/4)
	Phalaris paradoxa	ACCase (A/1)
Japan	*Alopecurus aequalis*	ALS (B/2), Microtubule (K1/3)
	Beckmannia syzigachne	Microtubule (K1/3)
Latvia	*Apera spica-venti*	ALS (B/2)
	Stellaria media	ALS (B/2)
Lithuania	*Apera spica-venti*	ALS (B/2)
Mexico	*Avena fatua*	ACCase (A/1)
	Phalaris minor	ACCase (A/1)
	Phalaris paradoxa	ACCase (A/1)
Netherlands	*Alopecurus myosuroides*	PSII (Ureas and amides) (C2/7)
New Zealand	*Avena fatua*	ACCase (A/1)
	Lolium perenne	ALS (B/2)
	Lolium perenne ssp. multiflorum	ACCase (A/1)
Norway	*Capsella bursa-pastoris*	ALS (B/2)
	Matricaria recutita	ALS (B/2)
	Polygonum persicaria	ALS (B/2)
	Spergula arvensis	ALS (B/2)

(continued)

Table 20.5 (continued)

Country	Weed species	Mode of Action (Based on site of inhibition)
	Sonchus asper	ALS (B/2)
	Tripleurospermum perforatum	ALS (B/2)
Pakistan	*Phalaris minor*	ACCase (A/1)
Poland	*Alopecurus myosuroides*	ACCase (A/1), ALS (B/2)
	Apera spica-venti	ACCase (A/1), ALS (B/2), PSII (Ureas and amides) (C2/7)
	Avena fatua	ACCase (A/1), ALS (B/2)
	Centaurea cyanus	ALS (B/2), Synthetic Auxins (O/4)
	Matricaria recutita	ALS (B/2)
	Papaver rhoeas	ALS (B/2)
	Tripleurospermum perforatum	ALS (B/2)
Russia	*Picris hieracioides*	ALS (B/2)
Saudi Arabia	*Lolium rigidum*	ACCase (A/1)
South Africa	*Avena fatua*	ACCase (A/1), ALS (B/2)
	Lolium rigidum	ACCase (A/1), ALS (B/2)
	Phalaris minor	ACCase (A/1), ALS (B/2)
	Raphanus raphanistrum	ALS (B/2)
Spain	*Alopecurus myosuroides*	PSII (Ureas and amides) (C2/7), ACCase (A/1), ALS (B/2),
	Bromus tectorum	PSII (Ureas and amides) (C2/7)
	Lolium rigidum	ACCase (A/1), PSII (Ureas and amides) (C2/7)
	Papaver rhoeas	ALS (B/2), Synthetic Auxins (O/4)
	Rapistrum rugosum	ALS (B/2)
	Sinapis alba	ALS (B/2)
Sweden	*Alopecurus myosuroides*	ACCase (A/1), ALS (B/2), Lipid (N/8)
	Apera spica-venti	ALS (B/2), PSII (Ureas and amides) (C2/7)
	Matricaria recutita	ALS (B/2)
	Papaver rhoeas	ALS (B/2)
	Stellaria media	ALS (B/2)
	Tripleurospermum perforatum	ALS (B/2)
Switzerland	*Alopecurus myosuroides*	PSII (Ureas and amides) (C2/7)
	Apera spica-venti	PSII (Ureas and amides) (C2/7)
Syria	*Avena fatua*	ACCase (A/1)
	Phalaris brachystachys	ACCase (A/1)
	Phalaris paradoxa	ACCase (A/1)

(continued)

Table 20.5 (continued)

Country	Weed species	Mode of Action (Based on site of inhibition)
Turkey	*Alopecurus myosuroides*	ACCase (A/1)
	Avena fatua	ACCase (A/1)
	Avena sterilis	ACCase (A/1)
	Bifora radians	ALS (B/2)
	Galium aparine	ALS (B/2)
	Phalaris brachystachys	ACCase (A/1), ALS (B/2)
	Sinapis arvensis	ALS (B/2), Synthetic Auxins (O/4)
United Kingdom	*Alopecurus myosuroides*	ACCase (A/1), ALS (B/2), Microtubule (K1/3)
	Avena fatua	ACCase (A/1), ALS (B/2), Anti microtubule mitotic disrupter (Z/25)
	Avena sterilis	ACCase (A/1), ALS (B/2), Antimicrotubule mitotic disrupter (Z/25)
	Lolium perenne ssp. multiflorum	ACCase (A/1), PSII (Ureas and amides) (C2/7), Long chain fatty acid (K3/15)
	Sonchus asper	ALS (B/2)
	Stellaria media	Synthetic Auxins (O/4)
United States	*Anthemis cotula*	ALS (B/2)
	Avena fatua	Cell elongation (Z/8), ACCase (A/1), ALS (B/2)
	Bromus japonics	ALS (B/2)
	Bromus secalinus	ALS (B/2)
	Bromus tectorum	ALS (B/2)
	Camelina microcarpa	ALS (B/2)
	Conyza canadensis	ALS (B/2), EPSP synthase (G/9)
	Descurainia sophia	ALS (B/2)
	Erysimum repandum	ALS (B/2)
	Kochia scoparia	ALS (B/2), Photosystem II (C1/5), Synthetic Auxins (O/4), EPSP synthase (G/9)
	Lactuca serriola	ALS (B/2)
	Lamium amplexicaule	ALS (B/2)
	Lolium perenne ssp. multiflorum	ACCase (A/1), ALS (B/2), EPSP synthase (G/9), Long chain fatty acid inhibitors (K3/15)
	Lolium persicum	ACCase (A/1)
	Secale cereale	ALS (B/2)
	Salsola tragus	ALS (B/2), EPSP synthase (G/9)
	Setaria viridis	ACCase (A/1), Microtubule (K1/3)
	Sonchus asper	ALS (B/2)
	Stellaria media	ALS (B/2)

20.6 Weed Management Perspective

20.6.1 Cultural Control

20.6.1.1 Preventive Measure

Weeds similar to crop in terms of life cycle, growth habits and duration of maturity are more challenging and should be effectively managed with preventive measures. Breaking chain of infestation of weed seeds by destructing of harvested seed with measures such as narrow windrow burning, baling and Harrington Seed Destructor can be integrated with other measures and may provide 95% weed control (Walsh et al. 2012). Separation of weeds seeds on threshing floor not only checks the seed movement to different fields but also can be used as feed for animals and poultry. *P. minor* seed collected at threshing flood and grain markets fetch 75% rate of wheat grains as it is a nutritious feed for poultry and other birds. Weed seed bank replenishment can also be checked by controlling weeds during fallow periods. Seed cleaning, use of clean seed drill, removal of weeds from bunds and channels are likely to reduce the initial weed pressure in field.

20.6.1.2 Stale Seedbed

False seed bed a cultural method checks initial weed pressure in crops. Here before sowing false seed bed is formed with two-three pre-sowing irrigations to trigger the germination of weed seedbank reserve and thereafter tillage operation or non-selective herbicide are applied to kill the emerging weeds. Stale seedbed method alone decreased *Alopecurus myosuroides* infestation by 25%, while stale seedbed preparation with late sowing and herbicide application reduced density by more than 75% in south-western Sweden. Stale seed bed has been applied to manage *Avena ludoviciana* infestation in wheat in India as delayed sowing will also reduce its emergence when temperature lowers in November–December and already emerged plants are controlled by field preparation or non-selective spray of glyphosate (Singh 2007). Singh et al. (1995b) reported that delayed sowing from November 10 to 30 reduced the fecundity of *A. ludoviciana* and provided better control with herbicide and higher wheat yield. Stale raised bed (furrow irrigated raised bed system) have been found more effective in managing herbicide resistant weed by mechanical weeding and lowers the cost of field preparation. The synergistic relation could be due to multiple factors, such as with stale seedbed, incorporation of crop residues was better and finer seedbed available that subsequently could improve the bioavailability and uniform distribution of prosulfocarb on the soil surface and also the delayed sowing, reduced the growth rate of *A. myosuroides* as lower air and soil temperature resulted in better herbicide uptake through the mesocotyl (Menegat and Nilsson 2019). Kanatas et al. (2020) evaluated possibilities of integrated weed management in barley with competitive cultivars, direct seeding, false seed bed techniques and herbicide use in Greece. The results showed that false seedbed reduced the dry weight of *Lolium rigidum* and *Phalaris minor* by 31–55 and 75–85%, respectively in comparison to direct seeding. Even, alone false seedbed reduced *L. rigidum* dry weight by 29–43% in comparision to combination of direct seedingwith application of post-emergence herbicide (Pinoxaden 45 g/ha). While, *Avena sterilis* biomass reduced by 77–93% under false seedbed with herbicide use as compared to combination of direct barley sowing with herbicide.

20.6.1.3 Tillage

In Canada (northern Alberta), zero tillage in spring wheat favored the weeds *Senecio vulgaris* L., *Galeopsis tetrahit* L, *Taraxacum officinale* Weber, *Polygonum scabrum* Moench, *Equisetum arvense* L., but *Polygonum convolvulus* L. in conventional tillage system (Arshad et al. 1994). A weed seedbank study from Italy (Ruisi et al. 2015) after 18 years of continuous mouldboard ploughing based conventional tillage (CT) or no-tillage (NT) with crop sequences involving continuous wheat, wheat–faba bean and wheat–berseem clover showed that tillage method altered both distribution and composition of weed seeds with in the soil profile. No tillage favoured *Papaver rhoeas*, *Lactuca serriola*, and *Phalaris* spp., while *Polygonum aviculare* favoured in conventional tillage. While, the highest weed seed bank density (16,000 seedlings m^{-2}) was recorded under wheat monoculture with reduction in weed diversity and more proliferation of *P. aviculare* followed by wheat–faba bean (10,000 seedlings m^{-2}) and wheat-berseem clover (6000 seedlings m^{-2}). Despite higher weed density (73 plants m^{-2}) in no tillage wheat (NTW) under wheat monoculture system as compared to minimum (40 plants m^{-2}) and conventional tillage (46.3 plants m^{-2}), the competition for water from weeds in NTW at tillering stage was lesser. The long-term rotation based (durum wheat–faba bean) study under different tillage methods (notill, reduced, and CT) and nitrogen fertilization showed that weeds such as *Conyza canadensis*, *Solanum nigrum, Papaver rhoeas*, *Fumaria officinalis,* and *Fallopia convolvulus* were more in reduced or conservation tillage, while *Anagallis arvensis* had the lowest seed bank in CT conditions (Fracchiolla et al. 2018). Under no till, weed population and dry biomass was higher by 39.7% and 50%, respectively as compared to conventional tillage in south east Poland (Gaweda et al. 2018). Scursoni et al. (2014) reported that weed diversity was higher in CT than in NT system in Argentina wheat. In winter wheat grown after maize under humid temperate climates (Canada), weed density followed the order NT < MT < CT. *Agropyron repens*, *L. perenne* and *T. officinale* were associated with CT, *P. annua* with MT, *Epilobium* spp., *Taraxacum officinale*, *L. perenne* and *M. arevensis* under NT. While, winter wheat grown after oilseed, *Epilobium* spp., *M. arvensis, S. arevensis* and volunteer rape were associated with NT and followed the density order as CT < MT < NT under without herbicide conditions (Streit et al. 2003). In winter wheat grown after oilseed rape, NT favored the volunteer oilseed rape as seeds were not buried by tillage but remained on the soil surface.

Moreover, climatic conditions affect water competence dynamics and higher relative water content was observed in untilled conditions (Santín-Montanyá et al. 2020). As compared to initial seed bank in the topsoil (4420 seedlings m^{-2}), *Galium aparine, Myosotis arevensis* and *Lamium* spp., were increased by 61% in chisel ploughing (5–15 cm; reduced tillage) with dead mulch (8–10 cm) consisting of triticale–vetch or rye–pea mixtures as compared to moldboard (25 cm; conventional

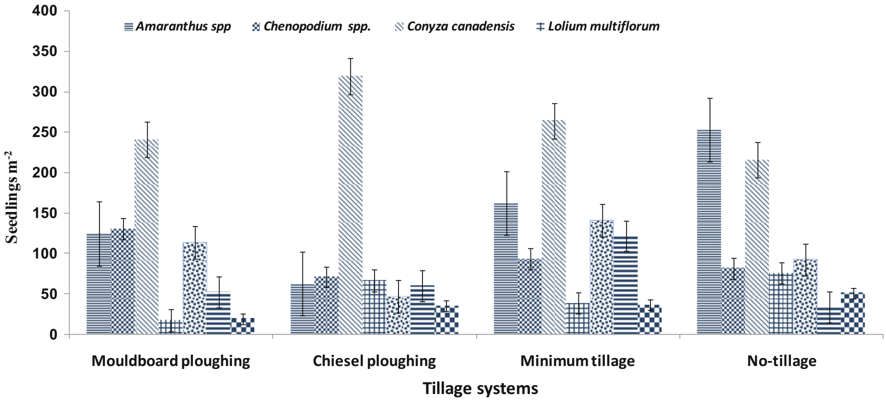

Fig. 20.1 Seedling densities (seedlings m^{-2}) of major weed species in soil seedbank (0–45 cm) under different tillage systems in winter wheat. (Baárberi and Lo Cascio 2001)

tillage) after two years in organically managed winter wheat–potato cropping system in Germany (Schmidt et al. 2019). In a long term study (12 years) with different tillage options consisting of no-tillage, minimum tillage (15 cm) and CT (mouldboard and chisel ploughing at 45 cm) in two different cropping system (continuous winter wheat and pigeon bean-winter wheat) demonstrated that tillage system had greater influence on weed seedbank size and composition than nature of crop rotation. Weeds were higher (Fig. 20.1) in depth 0–15, 15–30 and 30–45 cm for tillage under no till, minimum tillage and conventional mouldboard system, respectively in Central Italy (Barberi and Lo Cascio 2001). Punia et al. (2016) reported minimum weed seed bank under double zero tillage (Zt wheat-ZT-paddy) compared to other systems.

Further, about 60% of the total weed seedlings germinated from the top surface layer in no tillage compared to 43% in the other operated tillage system with more proliferation of *Amaranthus retroflexus* (L.) in former, whereas *Conyza canadensis* (L.) Cronq in later (chisel ploughing). Under tilled and rotation scenario, common lambsquarters and pigweed species attained large seed banks, whereas, yellow foxtail and field pennycress in no till. Further, under no till weed seed banks was 12,188 seeds m^{-2} as compared to chisel plow (7117 seeds m^{-2}) and moldboard plow (4770 seeds m^{-2}). While, huge seed bank under no till even after 18 years raised the significance of seed rain and seedbank management for sustainability of NT scenario (Légère et al. 2011).

In North China, different soil tillage methods (zero, harrow, rotary, subsoil, and conventional tillage) alter species, relative density, density and dry matter, while, harrow and rotary tillage were found comparatively superior for controlling weeds compared to other tillage system (Han et al. 2014). Tillage system in wheat (zero tillage, deep tillage, conventional tillage and raised beds) with preceded rice conditions (aerobic, alternate wetting and drying and flooded systems) significantly affected crop weed dynamics, establishment and yield-related traits of wheat. Broad leaf weeds namely *Chenopodium album* L. and *Rumex dentatus* L. dominated in bed sowing, conventional and deep tillage, while, *Phalaris minor* dominated under zero till wheat. Further, density of *C. album* was lowest after flooded rice, whereas densities of *P. minor* and *R. dentatus* were lowest after aerobic rice system in Pakistan (Farooq and Nawaz 2014). The aerobic rice followed by zero tilled wheat performed best at resource conservation scale, whereas, deep tillage could be employed to ameliorate the puddling-induced edaphic problems in rice–wheat system. The average weed biomass (year and crop rotation) was recorded minimum (4–5 gm^{-2}) in deep tillage, bed sowing (four rows with 60/30 cm) and bed sowing (six rows with 90/45 cm) followed by conventional tillage (8 gm^{-2}) and zero tillage (112.5 gm^{-2}). Higher weed biomass under zero till conditions associated with more density of weed in it (Shahzad et al. 2016).

In India, zero tillage reduced the densities of *Avena ludoviciana* (wild oats) and *C. album* but increased the density of *Medicago hispida* as compared to CT (Mishra and Singh 2012). The other studies indicated that ZT wheat under R-W system reduced the *P. minor* emergence and biomass accumulation considerably, but favored the broadleaf weed flora such as *R. dentatus* compared to CT (Sharma et al. 2004; Chhokar et al. 2007, 2009). The higher *R. dentatus* in ZT than CT method could be owing to lighter seed of *R. dentatus* with lower seed density (16.71 kg/hectoliter) as compared to *P. minor* (61.31 kg/hectoliter) and concentrated more on the surface soil following puddling operations in rice and subsequently emerge more in zero till wheat scenario (Chhokar et al. 2007, 2009, 2012). Higher *Rumex* population under zero tillage was also attributed to higher soil moisture and lesser depth of emergence (Dhawan 2005; Chhokar et al. 2007). Under ZT wheat, *Rumex* population was significantly higher (12,100–34,500 plants ha^{-1}) as compared to CT (1900–5000 plants ha^{-1}) and wheat yield reduction was recorded more due to competition from *R. dentatus* than *P. minor* (Sharma et al. 2004; Chhokar et al. 2007). Similarly, Chopra and Chopra (2010) also reported that *P. minor* density reduced by 72.5% under ZT but *Rumex spp.* density increased by 126.4% as compared to CT. However, ZT system recorded 22.5% higher weed dry biomass as compared to CT due to simulatenous germination of weeds along with wheat crop. Even, one may follow tillage operations early in the morning or later close to the sunset (<200 μmol m^{-2} s^{-1}) to prevent seed exposure to high light intensity (Ohadi et al. 2010). In winter wheat production system, *Salsola iberica* Sennen & Pau (Russian thistle), *Bromus tectorum* L. (downy brome), *Kochia scoparia* L. (kochia), *Amaranthus retroflexus* L. (redroot pigweed), *Sonchus arvensis* L (perennial sowthistle) and *Taraxacum officinale* Weber in Wiggers were associated with ZT, while, *Polygonum convolvulus* L. (buckwheat), *Chenopodium album* L. (lamb's-quarters), *Sinapis arvensis* L., *Cirsium arvense* (L.) Scop. and *Descurainia sophia* (L.) Webb ex Prantl (flixweed) in CT (Blackshaw et al. 2001a). The reduced seed vigour (with emerged barley plants 54–70%) increased the average weed biomass by 169–210% with reduction in barley yield by 16–21%, which was 8–10% under weed free conditions. While, three-times harrowing (pre-, early post- and late post-emergence) Einböck spring-tine harrow, strategy reduced the biomass of weeds by 72–75% but also damaged the crop (Rasmussen and

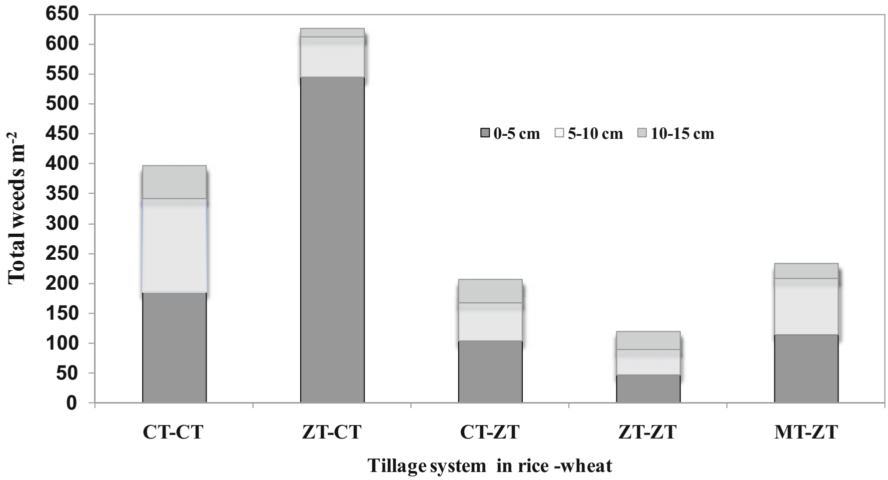

Fig. 20.2 Tillage driven weed dynamics in wheat in rice-wheat system (Punia et al. 2016)

Rasmussen 2000). Nature of tillage in rice i.e. dry direct seeded rice and puddle transplanted rice with intercropping of sesbania followed by different method of establishment such as CT wheat (CTW), ZT wheat (ZTW) and ZTW with full rice residue as mulch significantly affect the density and dry weight of weeds in wheat (Nawaz et al. 2017). The establishment techniques having various combinations of zero-tillage (ZT), minimum tillage (MT) and conventional tillage (CT), such as, ZT-ZT, ZT-CT, CT-CT, MT-ZT and CT-ZT significantly influenced total weed population m^{-2} with more distribution of weed seeds to a greater depth under CT-CT, CT-ZT followed by MT-ZT as compared to ZT-CT and ZT-ZT (Fig. 20.2) in rice-wheat cropping sequence (Punia et al. 2016). No tillage in continuous spring barley cropping system increased the total soil weed seed density and density of *Potentilla norvegica* L., *Capsella bursa-pastoris* (L.) Medic. and *Hordeum jubatum* L. in the top portion of the soil profile (Conn 2006).

20.6.1.4 Crop Rotation

The diverse crop rotation designed weed species communities by altering in the nature of tillage practice, tillage frequency, timing of tillage relative to crop and weed emergence, herbicide program (availability and dose) besides cropping practices, such as, crop seed rate, fertilization and irrigation practices (Liebman and Dyck 1993; Liebman 2000). The dynamics of community composition of weeds, soil seedbank, and weed density in three crop rotations showed that as compared to initial germinable weed seedbank density (1890 seeds m^{-2}) continuous durum wheat, canola/durum wheat/durum wheat and barley+ pea/durum wheat/durum wheat reduced weed seedbank by 23, 68 and 72%, respectively, in semi-arid Morocco regions under NT scenario (Tanji et al. 2017). A study based on crop rotation (soybean – winter wheat – rapeseed – winter wheat) with forecrop of winter wheat as soybean and winter rapeseed under two tillage systems (CT and NT) revealed that *Viola arevensis* frequently invading wheat seeded after winter rapeseed, while *Avena fatua* after soybean. After winter rapeseed (Gaweda et al. 2018), higher weed density (62.1%) and dry biomass (27.3%) was recorded in wheat indicating richer floristic composition as compared to after the previous crop of soybean in south east Poland. Therefore, nature of forecrop and its agronomic practices also reflect the nature of subsequent weed infestation in succeeding crop. Nelson et al. 2012 evaluated intercropping for weed suppression in organic based in Canada with spring wheat, canola, barley, and field pea monocultures compared with four-, three-, two- crop intercrops containing wheat. The findings showed that barley either an intercrop or a sole crop suppressed weeds more effectively as compared to all other intercrops and sole crops. The wheat plus canola intercropping showed the highest weed suppression of the two-crop as intercrops, while, pea and canola monocrops yielded the least under organic system. The broadcast mixed cropping of wheat + canola reduced dry weights of wheat associated weeds viz. *Chenopodium album* L., *Rumex dentatus* L., *Coronopus didymus* L. and *Phalaris minor* Retz. by 77.2, 77.4, 92.0 and 94.0%, respectively, as compared to sole wheat. Further, different wheat and canola intercropping ratios (1:1, 2:2 and 4:4 rows) reduced weeds dry weights by 81, 74, and 76%, respectively, in Pakistan (Naeem et al. 2012).

Légère et al. 2011 studied the effects of tillage system (moldboard ploughing, chisel ploughing, NT) and crop rotation (2-year rotation of barley–red clover) followed by 4-year rotation of barley–canola–wheat–soybean along with cereal monoculture) for eighteen years. The results showed that monoculture favored the more seed bank of barnyardgrass and green foxtail than rotation. Fried et al. (2012) conducted trait-based approach with synchronic and diachronic analysis to examine the relationship between traits and changing weeds status over a 30 years' period in France. The tillage intensity filtered weeds according to life forms, height, seed weight and dispersal, while herbicides scheduled species with delayed germination as escape mechanism under synchronic analysis. While, according to diachronic analysis small and light seeded weed can germinate during vegetative stage. The following trait syndrome could be ideal with crop rotation and developing herbicide pressure. In pea/rape-winter wheat-winter wheat, density and biomass of weeds increased with the tillage simplification. Under no till, most of weed seeds concentrated in top soil surface (0–5 cm), while, in deeper layers (5–10, 10–20 cm) in CT system (three times lesser seed bank). Further, more number of perennial and invasive species (*Conyza canadensis* L.) were observed under direct drilling conditions (Feledyn-Szewczyk et al. 2020). Goplen et al. (2017) studied the effect of six crop-rotation systems (corn–soybean–corn, soybean–corn–corn, soybean–wheat–corn, alfalfa–alfalfa–corn, soybean–alfalfa–corn and continuous corn) on giant ragweed seedbank dynamics and emergence patterns for 3 years in the mid-western United States. The corn and soybean rotations provide more favorable conditions to giant ragweed emergence than wheat and alfalfa based rotations. The crop rotations including winter oat-soybean rotation exhibited lesser effect on the italian ryegrass seed bank as compared to winter wheat or summer corn and can be utilized for *L. multiflorum* management under the future climate change (Pagnoncelli et al. 2020) in south region of Brazil. Kleemann et al. 2016 reported initial seedbank (4820 seeds m^{-2}) of rigid ryegrass (*Lolium rigidum*) can be managed effectively to reasonable levels (200 seeds m^{-2}) within three years by using oaten hay during initial year, followed by (fb) effective weed control in field pea (post-emergence application of clethodim fb crop-topping to prevent seed set of rigid ryegrass) and wheat crops in mid-north region of South Australia. In Pakistan, average (year and tillage) weed density in wheat was recorded minimum in sorghum-wheat (S-W) rotation (16 m^{-2}) followed by rice-wheat (31 m^{-2}), cotton-wheat (32.5 m^{-2}), moongbean-wheat (45.5 m^{-2}) and highest in fallow-wheat system (80 m^{-2}). Sorghum-wheat system strongly suppressed weed infestation in wheat and results were clearly evident from the second year of rotation (Shahzad et al. 2016). This variation of weed infestation in wheat could be associated with variable patterns of resource acquisition, competition, allelopathic interference, and tillage based soil disturbance that limits the growth and proliferation of weeds, especially in S-W as compared to moongbean–wheat. The optimal cropping systems could be planned to regulate weed seed banks, germination and reproductive responses for ecological control of *P. minor* (Xu et al. 2019). Diversification of rice-wheat system with cropping system with summer groundnut-potato-pearl millet (*Pennisetum glaucum* L.), summer groundnut-toria (*Brassica rapa* var. *toria*) + gobhi sarson, cotton-gobhi sarsontransplanted (*Brassica napus* sub sp. *Oleifera* var. *annua*), cotton-African sarson (*Brassica carinata* A. Braun), maize-potato-onion, maize-potato-summer moongbean, maize-wheat-summer moongbean, maize-wheat and cotton-wheat significantly reduced *P. minor* population 96.6%, 91.6, 88.8, 86.1, 88.8, 88.8, 86.1, 80.5 and 66.6%, respectively compared to conventional rice-wheat (Walia et al. 2011). The lowest herbicide resistant *P. minor* cases were recorded where growers followed diverse crop rotations than monocropping of rice-wheat sequence (Malik and Singh 1995). Thus diversification of the cropping system could modulate the extent of weed infestation and herbicide resistance in weeds to a greater extent but marketing problem of the produce, crop failure risk and food security concerns have restricted the wider acceptability of this aspect.

20.6.1.5 Cover Crops and Mulching

Cover crops Surface residue influence weed seed germination physically by reducing light interception, thermo moderation, impede seedling growth, chemical modification in the seed environment (Teasdale and Mohler 1993; Crutchfield et al. 1986). Besides, modulating emergence of weeds, presence of surface residue enhances weed seed predation rate and helps in depleting seed bank. In western Canada, mulches (6.0–10.7 t/ha) with hairy vetch (*Vicia villosa* Roth) showed best result with higher succeeding spring wheat grain yield with effective weed control under no-till organic wheat and reduced need for tillage for a period of 2 years (Halde et al. 2014). Kumar et al. (2011) showed buckwheat residue suppressed winter annual weeds emergence and growth by 22–72% and 0–95% without reducing wheat yield in Central New York. *Raphanus sativus* subsp. Oleiferus, *Sinapis alba* L., *Lupinus angustifolius* L., *Vicia sativa* L., *Avena sativa* L., *Amaranthus cruentus* L., *Fagopyrum esculentum*, *Helianthus annuus* L. and *Phacelia tanacetifolia* suppressed weeds under no-tillage resulting in reduced weed dry matter production. Further mechanical regulation of weed supreesive cover crops with a roll-chopper can be used to reduce herbicide use (Dorn et al. 2013).

The retention of corn residue as mulch reduced 42% of weed population and 50% in dry weights as compared with the non-mulched in wheat by reducing the light availability to weed, resultant in reduced growth (Tanveer et al. 2015). Paddy straw as surface mulch as 4 and 6 t/ha diminished the emergence of *R. dentatus* by 78 and 88%, respectively as compared to control (without mulch). Further, the reduction in emergence was improved with increased rice residue levels from 8 t/ha (95%) to 10 t/ha (99%) at 45 days after sowing (Kumar et al. 2013). However, majority of farmers in northwestern IGP burn rice straw/residuesfor proper seed drilling/sowing of succeeding wheat crop. The burning of straw leads to remarkable fluctuation in soil temperature that may inhibit or stimulate germination of weeds present in soil. However, *P. minor* population decreased due to straw burning as seed on surface were charred but increased temperature at deeper depths had no effect on stimulated germination. The soil remained moist and the weather remained cool and humid during November–December in North-Western India, so straw burning does not raise soil temperature to an extent to hamper the seed viability (Chhokar et al. 2009). While, reverse to it, burning of wheat straw in late April and early May resulted in 67.7% loss of *P. minor* seed (Yadav 2002). Lower dry biomass of *P. minor* was witnessed in conditions with zero till (ZT) in standing stubble (65 gm^{-2}), ZT after partial burning (72.5 gm^{-2}), ZT without stubbles (102 gm^{-2}), while maximum under conventional tillage (113.8 gm^{-2}) in wheat (Brar and Walia 2008). However, such kind of studies are lacking that relates *R. dentatus* response in wheat with in-situ straw burning. But surely, burning of rice straw decreases the effectiveness of soil-active herbicides like pendimethalin and isoproturon (Chhokar et al. 2009) along with greater emergence of *P. minor*. Chhokar et al. (2009) observed that 2.5 t/ha rice residue mulch not enough to reduce weed infestation, but 5.0 and 7.5 t/ha mulch load reduced thebiomass of *Rumex dentatus* by 17–55% as compared with ZT without residue. Direct seeded aerobic rice followed by wheat with full residue retention of rice as mulch reduced density and dry weight of weeds by 58.97 and 71.4%, respectively as compared to direct seeded aerobic rice followed by wheat but without residue, whereas 73.77% and 57.57%, respectively, as compared to puddled transplanted rice followed by conventional till wheat (Nawaz et al. 2017). The pre-emergence herbicides are generally less effective in no till residue retention systems due to presence of high levels of crop residue of previous crop (Borger et al. 2015). Increased carrier volume increased rigid ryegrass control from 23–68% with 50 l/ha to 68–82% with 100 l/ha associated with improved spray coverage from 9% to 26%, respectively with trifluralin. Mulch (2 t/ha) of transgenic cotton reduced weed density due to toxin release as compared to non-transgenic cotton, but negatively influenced soil properties and productivity of crops (wheat, canola and Egyptian clover) in Pakistan (Riaz Marral et al. 2020). Some studies results related to inhibition of *P. minor* germination and infestation in wheat cropsummaries in Table 20.6.

Table 20.6 Effect of rice residue on *P. minor* germination and infestation in wheat crop

References	Residue load (t/ha)	Reduction (%)	Remarks
Brar and Walia (2008)	5.0	23.92	Incorporation of 5 t/ha rice residue showed poor performance with 8.90% control as compared to retention
	6.0	46.47	
	7.0	54.03	
Chhokar et al. (2009)	5.0	28.5	Rice residue in lower amount (2.5 t/ha) failed to effectively suppress *P. minor*
	7.5	38.8	
Kumar et al. (2013)	6.0	45.0	Emergence of *Chenopodium album* and *R. dentatus was* inhibited by 83 and 88% at 6 t/ha and > 90% for both at 8–10 t/ha, respectively as compared to without residue mulch
	8.0	65.0	
	10.0	75.0	
Nawaz et al. (2017)	6–8	74.1	The reduction was recorded in direct seeding of rice followed by wheat under no-till with full residue retention scenario

20.6.1.6 Competitive Crop Cultivars

Wheat cultivars with quick germination, initial high vigour, and more plant height, rapid leaf expansion, more leaf elongation, extended canopy cover and improved root proliferation are more competitive against weeds (Lemerle et al. 1996; Worthington et al. 2015a, b; Lazzaro et al. 2019; Zerner et al. 2016). The inclusion of competitive crop cultivars to reduce the fecundity of weed species is of importance to manage weed seed banks and reduce over reliance on herbicides. In Poland, 14 winter wheat varieties were evaluated for competitiveness against weed under organic farming system and found that *Nateja* and *Jantarka* showed more competitive ability against weeds at three locations, while least competitive were *Ostka Strzelecka*, *Natula*, *Alcazar* and *Batuta* (Feledyn-Szewczyk 2012). Similarly, among 13 spring wheat varieties, four showed higher competitiveness against weeds and can be used in organic crop cultivation as compared to poor competitive cultivars i.e. *Monsun*, Parabola, Trappe, Tybalt (Feledyn-Szewczyk and Berbec 2013). In Italy, 160 wheat accessions were characterized for four traits associated with competitive ability against weeds viz. crop biomass prior to stem elongation, plant height, tillering index and morphology of flag leaf along with grain yield and thousand-grain weight traits. The findings showed eight accessions having reduced grain yield to plant height trade-off. The marker-trait associations with false discovery rates < 1% for biomass, plant height, thousand-grain weight, and grain yield, while, < 5% for all traits under consideration (Lazzaro et al. 2019). In North Carolina, 53 winter wheat cultivars and advanced experimental lines were assessed for morphological traits linked with weed-suppressive ability against italian ryegrass. The reduction in seed head density of Italian ryegrass was positively correlated with high crop vigor during ZG_{25}, ZG_{29} and ZG_{55} (Zadoks growth stage). Further, multiple regression models showed that about 71% of the variations in weed suppressive ability was determined by final plant height (ZG_{70} to ZG_{80}) and either plant height or vigor at late tillering stage (ZG_{29}). The average root length suppression of Italian ryegrass seedlings varied from 12% to 63% (Worthington et al. 2015a). Weed density is strongly influenced by wheat plants height, above-ground crop biomass during tillering stage, tillers number at the dough stage and differential responses were observed for wheat cultivars (Feledyn Szewczyk and Jonczyk 2017). In Pakistan, wheat cultivar Punjab 96 showed comparatively more tolerance against weeds than Inqalab 91 as yield losses in former due to different weeds (*Phalaris minor, Coronopus didymus, Rumex dentatus, Chenopodium album, Medicago denticulata* and *Poa annua*) were lower (10–55%) as compared to 60–76% in later one (Siddiqui et al. 2010). In Australia, 18 local cultivars and 68 spring wheat genotypes (high-vigour) were evaluated for weed tolerance/suppression and results have shown that height of the crop canopy at maturity positively correlated with the ability to suppress or tolerate weeds. Taller wheat cultivars were not only more tolerant to weed competition but also significantly suppressed weed-seed production. Further, early crop vigour based on crop canopy reflectance (NDVI) also performed similarly. However, trade-off exit as yield penalty associated with more competitive high-vigour tall or semi dwarf varieties could be the preferred where weeds have evolved herbicide resistance against the most of the recommended herbicides or under organic based agriculture (Zerner et al. 2016). The winter wheat lines (58) from southeastern United States were screened in an agar-based seedling bioassay for allelopathic effects against italian ryegrass. The important positively correlated competitive traits for weed suppressive ability included vigor and erect growth habit at tillering, more leaf area at stem elongation, higher plant height during tillering and stem elongation, along with grain yield tolerance (Worthington et al. 2015b). However, among the varieties, no significant correlation between weed suppressive ability/grain yield tolerance and allelopathy was found. This implies that breeders should focus on improving competitive traits within existing and adapted germplasm instead screening genotypes for higher allelopathic effect. A comparative study on competitive ability of wheat hybrid (Hystar), with cultivar (Illico) against associated weed showed that even with delayed sowing, dry weather conditions and at lower sowing rate hybrids having similar crop density as conventional cultivar (Milan et al. 2020). In Northern Greece, *Avena sterilis* (120 plants m^{-2}) showed more competitiveness as compared to *P. minor* (400 plants m^{-2}) in barley. Higher reductions in ear number and grain yield of barley were recorded in cultivars Klipper and Plaisant, while, least in Athinaida and intermediate with Thermi and Carina. Barley grain yield reductions by *P. minor* were 1%, 8%, 14%, 45% and 55%, for Athinaida, Carina, Thermi, Klipper and Plaisant, respectively, while with *A. sterilis* the corresponding losses in cultivars were 8%, 16%, 27%, 61% and 67%, respectively. Panicles of *P. minor* with competition from cultivars Thermi, Carina and Athinaida were 73%, 82% and 93%, whereas for *A. sterilis* the corresponding values were 52, 83 and 92, respectively as compared to cultivars Klipper and Plaisant. The interference of barley cultivars screened against weeds followed the order Athinaida > Carina > Thermi > Klipper ≥Plaisant (Dhima et al. 2000). Hansen et al. (2008) evaluated weed suppressive effects of 79 barley varieties by weed coverage assessments under weedy conditions and found suppressive index ranging from 12% to 55%. Further, varietal growth traits such as reflectance, leaf angle, leaf area index, and culm length can be used to screen varieties for this purpose. Significant variations are found among the numerous wheat cultivars for their weed competitive ability, in terms of dry weight and seed production (Travlos 2012; Worthington et al. 2015b). In Greece, among five wheat cultivars (Bob, Simeto, Meridiano, Cosmodur and Quadrato), Simeto showed higher efficacy in 50% reduction of the herbicide recommended rate (mesosulfuron +iodosulfuron) as it reduced biomass and seed production of wild oat by 81% and 98%, respectively compared to the untreated control plots (Travlos 2012). Further, the fecundity of *S. arvensis, P. rhoeas, A. sterilis* and *P. minor* in untreated plots of Quadrato cultivars was 21%, 23%, 31%, and 33% lower than in Cosmodur, respectively. Weed pressure is generally higher in organic, low-input based farming and initial years of conservation tillage systems and could reduce crop yield and quality. In this sense, increased crop competition can be integrated as low-cost option for improving weed control with reducing weed fecundity that survive with herbicide applications or organic system. Taller wheat varieties are generally better tolerators/ suppressors of weeds compared to shorter varieties (Lemerle et al. 1996). However, such traits are generally not desirable due to association with increased crop lodging and reduced grain yields. However, advanced genetic studies with agro ecological approaches for more appropriate wheat lines having suitable combinations of yield and competitive traits, which commonly show trade-offs, can be an additional tool in sustainable integrated weed management systems (Lazzaro et al. 2019).

20.6.1.7 Cultivars Blending

Several issues associated with monoculture are vulnerability to diseases, pests and weeds, yield instability, narrow down of genetic diversity, spatial biodiversity (Faraji 2011; Javad 2011). No doubt crop diversification provides numerous ecological benefits but required knowledge intensive crop management practices at system level and this could be poorly reflected at species level. But diversification is easy to manage at varietal level as mixtures of varieties within the field as functional diversification strategy to limit the gravity of problems associated with monoculture (Faraji 2011). Kaczmarek 2017 found *Bombona* cultivar characterized with significantly lower weed infestation compared to *Waluta* cultivar, while, sowing of the cultivars in the mixture increased the level of competitiveness against weeds. Science of cultivar mixtures relies on exploiting the potential of genetic diversity to buffer biotic and abiotic stresses. A comparative study from Mediterranean climatic regions on 19 common wheat types as 12 cultivars (modern and heritage cultivars), 2 six-cultivar mixtures, 4 three-cultivar mixtures, and one with all twelve cultivars (high diversity mixture). Heritage cultivars showed the highest weed suppression compared to modern cultivars, which could be due to more height, leaf area and shoot biomass. Further, mixtures with more number of components (six and twelve) tended to improve the overall crop performance in wheat as compared to the average of less diverse stand types. However, large scale adoption of cultivar mixtures required intensive knowledge of key cultivar traits associated with target agro-ecosystem service. Enhanced complementarity and synergy among these traits would maximize exploitation of the available genetic agro-biodiversity (Lazzaro et al. 2018).

20.6.1.8 Crop Competition

Maximizing uptake of resources in wheat could be driven by controlling spatial and temporal allocation of inputs such as fertilizers and irrigation. The competitive ability of *triticale* is higher as compared to wheat against the *Avena sterilis* and *Papaver rhoeas* (Kanatas et al. 2020), but less competitive than barley. Under high weed pressure, *triticale* can be grown instead of wheat. In USA, increase in wheat seeding rate (50–300 kg ha^{-1}) reduced *Erodium cicutarium* L. biomass and seed production by 53% and 95%, respectively, and subsequently, wheat yield increased by 56–98% (Blackshaw et al. 2000b). Similarly, increasing winter wheat density (from 40 to 60 plants/mrl) against jointed goat grass (*Aegilops cylindrica*) reduced biomass, head density and spikelet biomass by 27%, 37% and 47%, respectively (Yenish and Young 2004). Increased seeding rate (600 plants m^{-2}) reduced weed density by 64% as compared to crop-free check and 30% compared to local farmers' practices of 400 plants m^{-2} under 18-cm rows spacing (Kolb et al. 2012). The seeding density of wheat $> \sim 300$ plants m^{-2} can reduce herbicide rate (diclofop-methyl) by 0–40% (Lemerle et al. 2013) and showed higher competitiveness against *Lolium rigidum* in wheat belt of southern Australia. Increase in wheat seed rate (140, 160 and 180 kg/ha) significantly reduced *P. minor* dry weight (g m^{-2}) by 9.6, 24.9 and 28.1 as compared to 120 kg/ha (Mansoori 2019) at mean density of *P. minor* (0–30 plants m^{-2}). The criss-cross sowing reduced weed density and dry weight by 28 and 33%, respectively, compared to unidirectional line sowing (Hussain et al. 2017). Further, in comparision to the lowest seed rate (50 kg/ha), the highest seed rate (200 kg/ha) increased the grain yield by 37% (Hussain et al. 2017). Xue and Stougaard (2002) observed 45% reduction in biomass and seed production of wild oat with combined effect of large seed (spring wheat) and higher seeding rate. Increasing wheat seeding rate (175–280 plants m^{-2}) decreased wild oat panicle number (10%), biomass and seed production (20%). Even, large seeds of spring wheat upon emergence reduced wild oat panicles (15%), biomass and seed production (25%) in comparision with small seeds. Similarly, Kolb et al. 2012 observed that increased wheat plnat density from 400 to 600 plants m^{-2} reduced the *Sinapis alba* L. density by 30%. Evidences indicated that size-asymmetric competition in cereals can be regulated by increasing crop density and its distribution in two-dimensional space as compared to conventional row sowing. Spring wheat (600 m^{-2}) with grid sowing pattern reduced weed biomass by 60% in comparison to conventional density and distribution (400 m^{-2} with row) (Weiner et al. 2001). The alteration in crop row spacing and orientation can increase light interception by the crop and reduce the same for weeds (Holt 1995). Crop row orientation perpendicular to the path of the sun enhances crop resource use efficiency (water, nutrient and light) as a result leading to higher crop yields. Safdar et al. (2011) observed lesser weed biomass with 22.5-cm row spacing as criss-cross double row planting, as compared to 22.5 and 30-cm spaced single row or double row spacing, respectively. Narrower row spacing provides competitive edge to crop against weeds and also smother weeds emerging later on through fast canopy closure thus, providing less opportunity for photosynthesis and nourishment. Spring wheat density of 449 seeds m^{-2} reduced weed biomass by 38 and 27% in the uniform and random pattern than in rows. Under high weed pressure, shifting from normal rows (very high degree of spatial aggregation) to uniform and random pattern (distorted spatial aggregation) resulted in greater weed suppression (Olsen et al. 2005). A study based in western Canada showed that early cutting of barley for forage/silage effectively reduced wild oat populations and within two years, significantly reduced seed in the soil seed-bank (Harker et al. 2003). Wild oat density was higher under both the situation when barley was cut for silage later in its life cycle (normal silage) and when barley was grown for grain. Therefore, early crop cut as silage can be an effective weed management tool for wild oat, particularly in the conditions with restricted herbicide options due to the herbicide resistance aggrevation or in organic crop production systems. Further, seed production of wild oat was recorded more in semi-dwarf and/or hull-less cultivars such as Falcon (2380 m^{-2}) and CSC Earl (1600 m^{-2}) of barley as compared to taller hulled varieties such as AC Lacombe (800 m^{-2}) and Seebe (720 m^{-2}) indicating less competitive ability of former against wild oat (O'Donovan et al. 2000).

20.6.1.9 Resource Management

The management of crop fertilization (dose, method and time of application) can be integrated with other component for long-term effective weed management. The wild mustard density (15 plants m^{-2}) decreased grain yield of wheat by 22.1% and 43.1% for 90 and 210 kg N ha^{-1}, respectively. While, wild oat density (75 plants m^{-2}) reduced grain yield of wheat by 26.3% and 30.3% at 90 and 210 kg N ha^{-1}, respectively. The wild mustard density of 5, 10 and 15 plants m^{-2} reduced wheat grain yield by 21.4%, 32.2% and 40.2%, respectively as compared with control (Behdarvand et al. 2013) Increasing N rates increased the wheat grain yield in weed-free conditions, while with the infestation of wild mustard, the increasing N rates resulted in the increased competitive ability of wild mustard against wheat and yield losses. In another study, the wild mustard (15 plants m^{-2}) decreased the wheat grain yield by 31.6%, 34.4% and 53.3% in 90, 150 and 210 kg N ha^{-1}, respectively (Behdarvand et al. 2012). Nitrogen fertilization increased *Lolium multiflorum* L. competitiveness (100 plants m^{-2}) as reduction in wheat yield is increased from 20 to 30% with fertilization as compared to without nitrogen application. Further, nitrogen fertilization failed to modify dynamics of seedling emergence but augmented ryegrass growth and fecundity as individual fecundity (seeds/plant) increased from 118 to 190 with increase in nitrogen dose (Scursoni et al. 2012). At high dose of nitrogen (120 kg/ha), wheat showed more competitiveness than *P. minor* but not at low nitrogen (20 kg/ha), while, *A. ludoviciana*, remained more competitive against wheat under variable fertility levels and showed higher values of net photosynthesis as compared to *P. minor* under both stand (monoculture and mixture) types and nitrogen levels (Babu and Jain 2012). Increasing fertilizer (NPK) from 100 to 120% resulted in higher dry weight of *A. ludoviciana* and reduced efficacy of applied herbicides in wheat (Goudar 2018). A study on effect of N fertilization on ecophysiology and biomass of *Phalaris minor* and *Rumex dentatus* has shown that *Rumex dentatus* showed higher photosynthetic nitrogen use efficiency and photosynthetic energy use efficiency to the extent of 63.3–72.3% and 17.5–77.1%, respectively as compared with *P. minor* at two N levels (0 and 120 kg/ha). Still the average enhancement in photosynthetic rate was 12.7% at 120 kg N/ha (Singh and Singh 2015). Concussively, *R. dentatus* is physiologically better competitor and exhibited high resource use efficiency than *P. minor*. In a replacement series, *R. dentatus* had higher leaf area, specific leaf area, stomatal conductance, photosynthetic rate, transpiration rate that was translated into higher relative growth rate, aggressivity index and that reflected in greater competitiveness of *R. dentatus* against wheat than *P. minor* (Singh et al. 2013). In other words, wheat is more vulnerable to competition from *R. dentatus* than from *P. minor*. A study has shown that ammonium nitrate as nitrogen source broadcasted on the surface or banded 10 cm deep between each second wheat row along with fresh and composted cattle manure significantly influenced weed density of *Bromus tectorum, Thlaspi arvense* and *Descurainia sophia* as variable level of infestations were recorded in unfertilized (263, 55.5, 90), broadcast (366, 159.3, 156.5), banded (275, 96.3, 64.5) application of fertilizer (average of four years) along with manure (310.85, 77.3, 52.3) and compost (454.8, 136.3, 169.5), respectively for each weed. Further, ranking of the weed seedbank composted manure = broadcasted N fertilizer > fresh manure > banded application of N (Blackshaw et al. 2005). Point-injected nitrogen (ammonium nitrate) compared with broadcast N reduced weed seedbank by 29–62% (Blackshaw et al. 2004; Blackshaw 2004). Blackshaw et al. (2002) reported decrease in *Brassica kaber* and *Setaria viridis* shoot biomass by 11–46% and 10–22%, respectively, with point injecting N fertilizer relative to surface application. Fertilizer placement near to root zone instead of surface broadcast helps in increasing nitrogen uptake and competitiveness against weeds (Blackshaw et al. 2002) by extending the crop's size asymmetric competitive advantage. Further, nitrogen supply also significantly affected the weed makeup as *Sinapis arvensis* seemed to be favored by higher nitrogen, while, *Conyza canadensis* by low nitrogen conditions (Fracchiolla et al. 2018). Irrespective of weed density, banding of pig slurry decreased the weed dry biomass and nitrogen uptake by half compared to broadcasting of slurry. Further, nitrogen recovery by weed was reduced from 12% to 5% of the applied nitrogen by direct injection of slurry that reduced alter slurry: soil contact and the crop-weed competition balance in the favor of barley (Petersen 2003). Different fertilizing pattern (Fig. 20.3) in wheat significantly influence weed dynamics and diversity in a long term study (17 years) under winter wheat-soybean rotation in wheat (Tang et al. 2014). Higher weed density, biomass, Shannon-Weiner index under 'phosphorus and potash' as compared to 'nitrogen along with phosphorus'. Nitrogen management could be employed as integral component of cultural based weed management (Behdarvand et al. 2013). Designing efficient weed management strategies is essential to reduce herbicide over dependence. However, concerted efforts are required to know the effects of diverse crop management practices like fertilization and irrigation resources on weed-crop interactions.

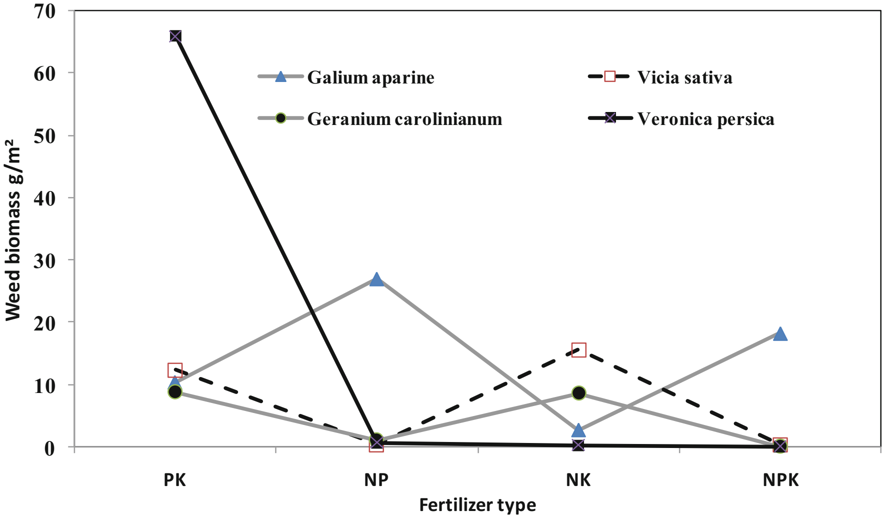

Fig. 20.3 Biomass (g m^{-2}) of different weeds under different fertilization treatments in wheat-soybean rotation in wheat (205 days after sowing) (Tang et al. 2014)

20.6.2 Physical

20.6.2.1 Weed Seed Destruction

Walsh et al. (2012) developed new tool as "Harrington Seed Destructor" a cage mill-based chaff processing unit to destroy weed seeds infesting grain crop chaff fractions with >95% efficacy of weed seed destruction while harvesting of grain crops (wheat and barley). Harrington Seed Destructor in wheat production regions of western and southern Australia reduced *Lolium rigidum* densities by 60% (Walsh et al. 2017).

20.6.2.2 Thermal

There are tools that use heating or freezing to rupture plant cells, which can result in plant death. Lasers, flaming, electricity, steam and microwaves are a few examples of thermal weed control (Upadhyaya and Blackshaw 2007; Tewari and Chethan 2018; Khan et al. 2018). In thermal weed control, weed seeds and seedlings are heated to kill them or reduce competitive ability. The heat transfer to the plant surface can through convection, condensation, radiation and conduction for a sufficient period of time. Flame weeding having intense heat wave kills weeds by rupturing the plant cells. Larger and more mature weeds require more intense heat and are difficult to kill with flaming. Flaming has been more effective against broadleaf weeds than grasses due to exposed growing tissue with more interception of heat and soft nature of former. The flaming of weed seedlings is delayed to expose maximum number of emerging weeds to intense heat. In addition, flame weeders have the advantage of their usage under wet conditions not suitable for mechanical weedings. Soil heating through stubble burning is a traditional agricultural practice of weed seed control. However, burning should be conducted under appropriate atmospheric conditions to minimize smoke impacts and protect public health.

20.6.2.3 Mechanical

Herbicides provide substantial and effective weed control but also have precarious impacts such as cause environmental pollution, herbicide resistance in the weeds, continuous use led to weed flora shift, contamination of groundwater etc. Mechanical control of weeds is a proven technique that can reduce the use of herbicides as well as improve the crop yield. Mechanized wed management employs agricultural machinery to perform weeding operation by various ways such manual weeding by hand hoe, cono weeder, cycle wheel hoe, peg type hoestraight bladehoe twin wheel hoe weeder and self propelled/power operated weeders such as rotary weeders (Tewari and Chethan 2018). Mechanical weed control options like hand hoeing, use of bar harrow and hand pulling of weeds decreased the weed biomass by about 64 to 72% and led to increase in grain yield by about 29% (Jabran et al. 2012).

20.6.3 Biological (PGPRs/Bio-Herbicides) Based Weed Management

Akbar and Javaid (2012) observed herbicidal action of metabolites from fungi (*Drechslera hawaiiensis, D. biseptata, D. holmii and D. australiensis*) which that notably reduced seed germination, root and shoot growth of *P. minor*. Wheat seed treatment with *Bacillus subtilis* and *Providentia rettgeri* spp. not only increased plant height of wheat compared to untreated, but also lowered herbicide toxicity; the results on *P. minor*; however, were inconsistent. Among the different fungi, *D. australiensis* resulted up to 94% reduction in growth parameters. While, *D. hawaiiensis* reduced more than 60% length and dry biomass of shoot. So, *D. australiensis* metabolites can be used as effective herbicides (pre-emergence) to tackle the herbicide resistant *P. minor* populations. Further, four *Drechslera* spp. culture filtrates were also effective against *Rumex dentatus* L. in wheat. These culture filtrates caused 30–58% reduction in weed biomass leading to 6–22% increase in wheat grain yield. *D. australiensis* and *D. hawaiiensis* showed superior action with more than 55% reduction of weed biomass and can partially be substituted or integrated with other management practices in organic wheat production (Akbar and Javaid 2015). Dar et al. (2020) found consortia of *Pseudomonas* strains C3 (B11xT75), C4 (T19xT24), C9 (B11xT24xT75) and C11 (B11xT19xT24xT75) reduced root length and increased *P. minor* seedling mortality by more than 50% as compared to the uninoculated control. While, concurrently increased leaf greenness, shoot length, fresh and dry biomass along with root length by 21, 42, 80, 81.5 and 100%, respectively in wheat. These strains act as plant growth promoting rhizobacteria and possessed characteristics of siderophore production, phosphorus solubilization and enzymatic activity (oxidase, ACC-deaminase and catalase). The combined application of *Pseudomonas aeruginosa* and *Trichoderma harzianum* strain reduced shoot length of *Avena fatua and Phalaris minor* by 40 and 30%, root length by 28 and 22% and fresh biomass by 31 and 29%, respectively (Mustafa et al. 2019), beside enhancing growth, yield and physiological parameters of wheat. These findings emphasize the significance of integrating the use of microbes with reduced herbicide rates for sustainable weed control and crop production.

20.6.4 Enhancing Weed Seed Predation

Weed seed predation is a potential contributor in ecological weed management tactics that is significantly influenced by agronomic and environmental factors (Davis et al. 2013). Weed seed predation is an essentially site-specific phenomenon. The mean annual weed seed predation rates of the combined action of invertebrate and vertebrate predators of giant ragweed, velvetleaf and giant foxtail were 31 ± 1.6%, 37 ± 1.4% and 53 ± 1.4%, respectively. Ichihara et al. 2011 studied post-dispersal weed seed predation of Italian ryegrass (*Lolium multiflorum* Lam.), after paddy in upland wheat fields. Loss in weed seed during four months estimated in the field interior areas and boundary strips was to be 35–43% and 42%, respectively. The seed predators in the field interior areas were rodents or birds in vertebrates) and crickets along with ground beetles as invertebrates and made substantial contribution in the depletion of post-dispersal seeds of Italian ryegrass. The weed seed predation is more in ZT field due to occurrence of seeds on the soil surface. However, extent of weed seed predation also varies depending on weed flora.

20.6.5 Allelopathy in Weed Management

Allelopathy can be utilized by rotating allelopathic crop in rotation, use of cover crops, mulch, green manuring, intercropping (Jabran et al. 2015; Bertholdsson 2005; Bhowmik and Inderjit 2003). The aqueous extract of sunflower leaves significantly reduced the number of *Rumex* plants m^{-2}, however inhibitory effect was concentration dependent (80% vs 100%). The leaf extract (80%) reduced plant number from 24 to 13 and dry biomass by 68%, while 100% aqueous extract, reduced plant number to one third and biomass by 97% as compared to control. Further, plants remained after spray was shortstature, weak with lower leaf area (Anjum and Bajwa 2007). The leaf extract of sunflower can be used as potent chemical for controlling for *Rumex dentatus* in wheat fields. Moss et al. 2007 found allelopathic triticale cultivar "Dinaro" (wheat-rye hybrid) and wheat cultivar "Nimbus" significantly reduced the black-grass biomass by half as compared to low allelopathic activity based ones and could contribute in resistance prevention or management in black-grass (*Alopecurus myosuroides).* Further, wheat-rye translocation lines can be explored for developing high allelopathic wheat lines**.** In wheat mainly 2, 4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one, *p*-Hydroxybenzoic, *cis-p*-coumaric, *trans-p*-coumaric, syringic, vanillic, *trans*-ferulic, and *cis*-ferulic acids are the important allelochemicals (Wu et al. 2000b, b; Lodhi et al. 1987)**.** The seedling allelopathic effect of 453 wheat accessions (from 50 countries) against annual ryegrass, showed variable ryegrass root growth inhibition (9.7 to 90.9%) (Wu et al. 2000a).

20.6.6 Biotechnological Approaches

20.6.6.1 Herbicide Tolerant Cultivars

The introduction of new chemistry for weed control is almost not observed for the last two decades. Under such circumstances, we have to explore the possible use of some less selective or non-selective herbicides through imparting herbicide resistance or tolerance in crop genotypes. Bhoite et al. 2019 recommended simple additive–dominance gene effects governing metribuzin tolerance in wheat and genes associating with photosynthesis system II assembly factor, cytochrome P450, glutathione S-transferase, glycosyltransferase, metabolic detoxification of xenobiotics, ATP-binding cassette transporters and glutathione peroxidase were involved on different chromosomes (2A, 2D, 3B, 4A, 4B, 7A, 7B, 7D) resulted in metribuzin tolerance. Herbicide-tolerant varieties can also be developed by genome editing at the wheat acetolactate synthase (ALS) genes Pro-174 codon endowed resistance to nicosulfuron herbicide (Zhang et al. 2019). Martins et al. 2015 demonstrated wheat varieties with Imi1 allele showing resistance to the imidazolinone herbicide imazamox. However, the samples from Eastern Oregon exhibited allele movement between IMI-resistant wheat and jointed goatgrass (*Aegilops cylindrica*) via hybridization and backcross events. So efforts are needed in this region to reduce IMI-resistant hybrid backcross plants and prevent introgression of the IMI-resistance allele.

20.6.6.2 Quantification of Resistance and Gene Silencing

Liu et al. (2015) reported Pro197Glu substitution endowed wide-spectrum resistance across ALS inhibitors (fold) viz. tribenuron (318), pyrithiobac sodium (197), pyroxsulam (81), florasulam (36) and imazethapyr (11) in water chickweed (*Myosoton aquaticum* L.) a aggressive broad-leaved weed in wheat fields of China. *Galium aparine* L. a dicot weed of wheat in China showed high resistance levels (2.92 to 842.41-fold) to tribenuron-methyl having five diverse ALS mutations i.e. Pro-197-Leu, Pro-197-His, Pro-197-Ser, Asp-376-Glu and Trp-574-Leu and that consequently made it resistant to flumetsulam, flucarbazone-sodium, pyrazosulfuron-ethyl, triazolopyrimidine sulfonylurea, sulfonylamino-carbonyl-triazolinone, pyribenzoxim, pyrimidinyl thiobenzoate, and imidazolinone imazethapyr (Deng et al. 2018). In Iran, Acetyle-CoA Carboxylase inhibiting herbicides (diclofop-methyl and clodinafop-propargyl) are commonly used in wheat but now *Phalaris brachystachys* in Golestan Province has shown resistance against it with resistance ratio 2.7–11.6 (Golmohammadzadeh et al. 2019) and could be due to Cytochrome P450 monooxygenases based enhanced metabolism. Bi et al. (2016) showed fenoxaprop-P-ethyl resistant *Alopecurus japonicas* resistant to mesosulfuron-methyl (39.9-fold) and resistance to both mesosulfuron and fenoxaprop is due to a substitution of Trp 574 to Leu in ALS and amino acid substitution of Ile1781 to Leu in Accase. Further, the population became resistant to other herbicides such as ACCase (sethoxydim, clethodim, clodinafop and pinoxaden) and ALS (pyroxsulam, flucarbazone-Na and imazethapyr) inhibitors but sensitive to the haloxyfop-R-methyl (ACCase herbicide). Zhang et al. (2017) found multiple mechanisms involved in fenoxaprop resistance in Italian ryegrass from China as mutations involving Ile-1781-Leu and Asp-2078-Gly substitutions (target site) in the carboxyl-transferase (CT) domain of acetyl-coenzyme A carboxylase and cytochrome P450–mediated metabolism of herbicides (non target site). Further, the biotype exhibited resistance against haloxyfop, quizalofop, sethoxydim and clodinafop. About 17% of total *Alopecurus myosuroides* population (53) exhibited resistance against ACCase inhibitors with a mutation at Ile-1781 position, but not against ALS inhibitors in Denmark. Further, seed bioassay is not sufficient to detect resistance with residual herbicides such as pendimethalin (Keshtkar et al. 2015). Raghav et al. (2018) found non-target site based resistance in littleseed canarygrass (*P. minor*) against isoproturon as lacking of mutations in herbicide binding region of psbA gene of isoproturon resistant biotypes. Comont et al. (2019) studied presence and magnitudes of fitness costs in *Alopecurus myosuroides*, an ideal grass weed species having evolution of resistance against seven modes-of-action herbicides. The study has shown during vegetative growth, resistant plants demonstrated greater intraspecific competitive effect and tiller lengths as compared to susceptible, whereas later one during flowering allocated relatively more biomass to reproductive tissues. Under gradient of nitrogen deprivation, resistant types produced 27% less seed heads/ plant along with 23% decline in total seed head length as reproductive cost of resistance. Mobli et al. (2020) evaluated effect of wheat plant densities (0, 82 and 164 plants/m^2) on seed production of glyphosate-resistant (Gly R) and glyphosate-susceptible (Gly S) populations of annual sowthistle (*Sonchus oleraceus* L.). In absence of competition from wheat, the Gly S biotype produced 80% higher seeds (46,050 per plant) than Gly R biotype but without any difference in leaves and biomass. However, with wheat density of 82 plants m^{-2}, seed production of Gly S and Gly R biotypes was decreased by 69 and 33%, respectively, as compared to without competition situation, and further increase in wheat density to 164 plants m^{-2} reduced more the number of seeds in the Gly S biotype (81%) only in Australia.

20.6.7 Chemical Weed Control

20.6.7.1 Selection of Herbicides

Herbicide applications in sequences (pre-and post- emergence) would be better alternative as compared to their alone applications to manage herbicide resistant weed biotypes (Table 20.7). Mustard is widely grown as intercrop with wheat and barley, in such fields the possible pre-emergence herbicide option can be pendimethalin and post emergence options can be pinoxaden (grass weed control) and isoproturon (grass and broad-leaved weeds control). Additional for sugarcane

Table 20.7 Global herbicide options in wheat and barley with their time of application (Herbicide mentioned with ^{xB}are not or less selective in barley)

Herbicide Mode of action	Chemical group	Herbicides	Application timing	Nature of weed flora control
Synthetic auxins	Aryloxyalkanoic Acid	2,4-Dichloro phenoxyacetic acid	POE	BLWs
	Arylpicolinate	Halauxifen	POE	BLWs
	Pyridine carboxylic acid	Fluroxypyr	POE	BLWs
ALS inhibitor	Sulfonylurea	Sulfosulfuron^{xB}, Tribenuron, Metsulfuron, Triasulfuron, Mesosulfuron^{xB}, Iodosulfuron^{xB}	POE	Grass and BLWS
	Triazolopyrimidine	Florasulum	POE	BLWs
5-Enolpyruvyl shikimate 3-phosphate synthase	Glycine	Glyphosate	Pre plant	All types
		Glufosinate	Pre plant	All types
Photosystem-I-electron diversion	Bipyridylium	Paraquat	Pre plant	All types
PS II inhibitor	Phenyl urea	Chlorotoluron^{xB}, Isoproturon	PRE and POE	Grass and BLWS
	Triazine	Metribuzin^{xB}, Terbutryn^{xB}		Grass and BLWS
	Subsituted urea	Metaxuron^{xB}	PRE and POE	Grass and BLWS
ACCase inhibitor	Aryloxyphenoxy propionate	Clodinafop^{xB}, Diclofop, Fenoxaprop-P^{xB}	POE	Grass
	Cyclohexanedinone	Tralkoxydim^{xB}		
	Phenylpyrazoline	Pinoxaden		
Microtubule-assembly inhibitor	Dinitroaniline	Pendimethalin	PRE	Grass and BLWS
PPO Inhibitors	Triazolinone	Carfentrazone-ethyl	POE	BLWs
	N-phenylphtalimide.	Flumioxazin^{xB}	PRE	Grass and BLWS

(continued)

Table 20.7 (continued)

Herbicide Mode of action	Chemical group	Herbicides	Application timing	Nature of weed flora control
Carotenoid biosynthesis	Pyridinecarboxamide	Diflufenican	POE	Grass and BLWS
	Diphenylether	Aclonifen	PRE and POE	Grass and BLWS
HPPD	Isoxazole	Isoxaflutole	POE	Grass and BLWS
Very long chain fatty acids inhibitor	Isoxazoline	Pyroxasulfone^{xB}	PRE and POE	Grass and BLWS
	Oxyacetamide	Flufenacet^{xB}	PRE and POE	Grass

and wheat intercropping sulfosulfuron + metsulfuron mixture can be used (Kumar et al. 2017; Chhokar et al. 2012).

20.6.7.2 Spray Technology (Spray Time as per Crop/Weed Stage, Dose and Method of Application)

The serious and widespread development of resistance in different weeds was cumulative effect of several factors associated with monocropping, long period of continuous spraying of the same chemical, poor application method and sub-optimum doses, faulty spray techniques, ecological niche such as rice straw burning in case of *P. minor* (Malik and Singh 1995; Chhokar and Malik 2002; Singh 2007; Chhokar et al. 2009; Chhokar et al. 2012; Chhokar et al. 2018). The continuous no till in wheat based cropping system acted as filter for weeds and has resulted into build-up of specialized weed complex as *Avena fatua* L., *Bromus tectorum* L., *Setaria* spp., *Kochia scoparia L.*, *Lactuca serriola* L. and *Salsola tragus* L. in US Great Plains. Further in each field every year, glyphosate is being applied three to four times (Kumar et al. 2014). Such repeated spray should be avoided to prevent the resistant development and shift of weed flora (Jha et al. 2016).

Sorghum residue at rates 3.5–5.3 t/ha could compensate the half dose of herbicide as *Sorghum bicolor* L. residues in combination with 50% rate (160 g/ha) of mesosulfuron and iodosulfuron resulted in similar yield and weed control as with the recommended herbicide dose in wheat (Lahmod and Alsaadawi, 2014). But, reduction in herbicide dose/usage of lower dose could lead to faster herbicide resistance evolution (Manalil et al. 2011) as lower doses of diclofop endowed resistance evolution in susceptible rigid ryegrass biotype in wheat and even shown cross resistance to other herbicides which were not applied yet. As lower herbicide rates led sizeable survivors of rigid ryegrass and this cross-pollinated species have the potential to accumulate all minor herbicide resistance traits present in the population. Therefore, recommended herbicide rate should be used for ensuring satisfactory weed control and also minimizing the likelihood of minor herbicide resistance traits causing faster evolution of herbicide resistance (Manalil et al. 2011).

Pyroxasulfone a soil-applied herbicide (0.05–0.15 kg a.i. ha^{-1}), flufenacet and flufenacet with metribuzin in winter wheat resulted in high level of activity against weeds especially against Italian ryegrass. The pre-emergence application of diclofop controlled Italian ryegrass by 57%, while, flufenacet with metribuzin combination controlled 73–77%, while, with post-emergence applications control was 78% and 77–99%, respectively (Koepke-Hill et al. 2011). Hulting et al. (2012) reported that pyroxasulfone applications in winter wheat controlled Italian ryegrass by 65–100% which was similar to control achieved by flufenacet and flufenacet + metribuzin applications but more than by diuron. Reis et al. 2017 evaluated the effect of salicylic acid in attenuating the phytotoxicity associated with application of flumioxazin in wheat and observed the mixture of salicylic acid (0.5 mM) with flumioxazin (40 g ha^{-1}) reduced phytotoxicity by 30–50% with improved yield. In the regions with poor control history of *P. minor*, sequential application of pre-emergence pendimethalin (1.5 kg/ha) *fb* mesosulfuron + iodosulfuron (14.4 g/ha) as post-emergence provided 88–93% control (Kaur et al. 2019).

20.6.7.3 Precision Herbicide Application

Site-specific weed management employs customized control herbicide applications. Remote sensing can be a convenient alternative option for weed scouting to optimize weed management effectively. Remote sensing mainly employs satellite or aircrafts for capturing field data. Remote sensing based on satellite- is appropriate for surveying large areas as well as large-scale yield monitoring (Zhang et al. 2005). However, imagery of satellite lacks precision in measuring or data documentation of small areas, such as weed detection, spatial distribution of inputs/herbicides, and herbicide toxicity estimations. To tackle these lacking the high- resolution imageries are required, which can be realized by using manned/unmanned aircrafts or ground vehicles having closer observations. Ground-based sensors use machine vision for precise herbicide delivery and weed detection as well (Hagger et al. 1983). Thus ground-based optical sensors can reduce the herbicide load by identifying and discrimination of plants based on the surface reflectance (Andújar et al. 2011). Hagger et al. (1983) used the reflectance-based plant sensor, which measure the radiance ratio of red and near infrared, for spraying on weeds. The radiance ratio is usually more for green surfaces as compared to soil. Herbicide applications based on optical/reflectance-based sensors have been studied worldwide (Lamm et al. 2002; Midtiby et al. 2011; Singh et al. 2020). However, optoelectronic sensors fail to differentiate the weed species and can be of use wherever broad-spectrum herbicides are to be used. Whereas, site-specific herbicide applications need a more targetted approach to apply selective herbicides for particular weed situations. Integration of unmanned aerial systems (UAS) offer more opportunities as compared to satellite- or manned-aircraft-based remote sensing and ground vehicle-based sensing (Singh et al. 2020). The applications of UAS are on rise in agronomic cropping systems, forestry and rangeland ecology (Laliberte et al. 2010; Singh et al. 2020). Hyperspectral and multispectral imaging sensors on unmanned aerial vehicles can be used to identify and differentiate weeds species (Peña et al. 2013; Nugent et al. 2018). These imaging sensors can provide important information which is not feasible with RGB cameras. Hyperspectral imaging is generally used to classify vegetation because of more bands than multispectral sensors. It collects reflectance data over a broad spectral range through narrow bands (10 nm) (Mulla, 2013). Hyperspectral remote sensing distinguished *T. aestivum* from *Glycine max* L and other broadleaf weeds (Gray et al. 2009). It can also be utilized as to differentiate between herbicide- susceptible and resistant weed populations. Nugent et al. (2018) utilized hyperspectral imagery to distinguish *Kochia scoparia* (L.) Schrad. biotypes resistant to dicamba or glyphosate from susceptible biotypes and differential reflectance were observed near 720 nm for dicamba-resistant and susceptible *kochia*. The herbicide-resistance management is likely to be easier, if resistant weeds could be detected at early stages of resistance evolution in fields. Greater efforts are needed in this novel area to develop efficient hyper-spectral imagery-based early herbicide-resistant weeds detection systems.

20.6.8 Integrated Weed Management (IWM) Practices for Wheat and Barley

The best weed management practices are established on the concept of 'diversified weed control tactics'. Its adoption will help in reducing the herbicide selection pressure thus reducing the spread of resistance seed, and preventing weed seed bank additions are the important approaches to tackle herbicide resistance issues (Norsworthy et al. 2012; Anderson 2007). IWM integrate various practices, including chemical approaches, to reduce the adverse effect of weeds on crops and seed production potential of weeds. It involves practices such as enhancing crop competitiveness against weeds, fields scouting for weed infestation and intensity, and implementing crop rotations including silage, forage legumes as well as oilseed crops in rotation with cereals (Buhler 2002; Anderson 2007). The early crop emergence has an edge over the weeds and it can be achieved by seeding the seeds having vigor at optimum depth. Also, proper timing and placement of fertilizers ensure better acquistion by crops and lesser by weeds. Growing competitive crop varieties with higher seeding rates, promoting early crop emergence by seeding high quality seed at relatively shallow depths, and strategically fertilizer application improves on the whole crop competitiveness, and thus reducing the requirement for herbicide applications (O'Donovan et al. 2007). Moreover, the competitive cropping systems also ensure greater flexibility in herbicide use through reduced doses and frequencies. With a competitive cropping system (Blackshaw et al. 2005) such as barley-field pea–barley-field pea rotation in a zero-till production system had weed biomass, crop yield, and weed seed bank comparable with the

50 and 100% in-crop herbicide rates. At the one fourth herbicide rate, seed production of wild oat reduced by 91–97% when, tall barley cultivars with double seed rates were in rotation with canola and field pea as compared to short barley varieties at standard seeding rates under barley monoculture in low management system. Moreover, at the same herbicide dose, wild oat biomass was reduced 2- to 3-, 6- to 7- or 19-fold when single {1 X (normal seed rate) vs. 2 X, Short vs. Tall cultivars, or Continuous barley vs. Rotation with canola and field pea), double (1 X-Short- vs. 2 X-Tall, 1 X-Continuous barley vs. 2 X-Rotation of batley-canola-field pea, or Short- Rotation of batley-canola-field pea vs. Tall- Rotation of batley-canola-field pea), or triple (1 X-Short-Continuous barley vs. 2 X- Tall- Rotation of batley-canola-field pea) treatments were pooled, respectively at different Canadian Prairie locations. The synergistic interaction of favorable cultural practices reduced the wild oat emergence, biomass and seed production, and subsequently increased barley grain yield (Harker et al. 2009). Cropping systems involving no- tillage, diverse crop rotations, competitive crop cultivars, higher seeding rates, site specific fertilizer management along with cover crops can effectively manage weeds with targeted but limited application of herbicides (Blackshaw et al. 2008; Bagavathiannan and Davis 2018).

20.7 Conservation Agriculture and Weed Management

Under CA, weed control is challenging task than in conventional tillage (CT) due to absence of tillage support and pre-plant incorporation of herbicides. Sudden shift in tillage considerably affect weed dynamic and weed seed distribution in the soil. In no- till the most of the weed seeds are on the soil surface and in absence of herbicide use weed seed bank is enriched regularly. This is the reason qualifying high infestation of weeds under zero tillage especially during initial years. Zero till (ZT) in wheat favor more proliferation of *Rumex dentatus, Polypogon monspeliensis* (Chhokar et al. 2007) and earlier emergence of *A. fatua*, *C. album* (Bullied et al. 2003) but significantly the *P. minor* population conservation tillage promoted conventional tillage. Further, surface residue influence weed seed germination physically by reducing light interception, thermo moderating effect, impede seedling growth, or by chemical modification in the seed environment (Teasdale and Mohler 1993; Crutchfield et al. 1986). Besides, modulating emergence of weeds, presence of surface residue enhances weed seed predation rate and helps in depleting seed bank. As in the ZT system weed control is not supported by tillage or mechanical interculture so there is increased reliance on herbicides. Further, very few options in post emergent herbicides with greater vulnerability to herbicide resistance promoted pre-emergence herbicides as reliable option. But these herbicides are less effective in ZT system due to presence of crop stubble/residue load that intercept considerable amount of applied herbicides (Chauhan and Abugho 2012; Chaudhary et al. 2019). So there is need to optimizing spray volume and time of application along with droplet size under these conditions for better weed control (Chaudhary et al. 2019). Further, proper selection of herbicide formulations in heavy residue retention situation could also improve efficacy of herbicides. Sindhu et al. (2017) found synergistic integration of ZT + residue retention (8 tons/ha) along with higher seed rate (125 kg/ha) coupled with pre-emergence herbicide mixture of pendimethalin + metribuzin at 1.50 + 0.210 kg/hareduced weed population significantly. Nutrient management is also considered as important aspect in partial rice-wheat system CA where, high amount of residue may lead to partial immobilization of nitrogen. Generally, farmers applied higher amount of nitrogen fertilizers in wheat to avoid initialyellowing of crop or temporary immobilization. A study revealed that by increasing 20% more fertilizer compared to recommended fertilizer dose, reduced by 30–50% herbicide efficacy and so as yield` by more than 30%. Higher dose of applied fertilizer benefited more the weeds compared to wheat and significantly increased weed density along with dry weight of weeds (Goudar et al. 2017).

20.8 Climate Change and Response of Wheat and Barley Associated Weed

Climate change implies the changes in the state of climate such as increase of temperature and or atmospheric CO_2 level that can be assessed by appropriate analytical and statistical methods on long term basis (IPCC 2007). Increase in atmospheric CO_2 level, temperature and precipitation will have pronounced effect on plant growth and productivity in near future (Lobell et al. 2011). Since 1958 atmospheric CO_2 has increased by 24% to a current level of 387 μmol mol^{-1} and current projection indicate a CO_2 from 600 to 1000 μmol mol^{-1} by 2100 (IPCC 2007).

20.8.1 Growth and Distribution of Weeds

Ongoing increase in atmospheric CO_2 should encourage leaf photosynthesis in C_3 plants by increasing CO_2 concentration gradient from air to leaf interior and by reducing photorespiration (Ziska et al. 1999). While in other photosynthetic C_4 pathway already an internal biochemical pump for concentrating it at the carboxylation site hence, it is expected that C_4 plants should be saturated at the current atmospheric CO_2 level, whereas, C_3 plant would continue to respond photosynthetically to the elevated atmospheric $CO_{2.}$ Out of the 18 world's worst weeds 14 are C_4 plants (Holm et al. 1977). Because C_4 photosynthetic pathway overly representative in problematic weed species so many experiments are concerned with weed competition and rising CO_2 have been reported on C_3 crop and C_4 weed interaction. However, many of the troublesome weeds for a given crop are genetically similar and frequently possess the same photosynthetically pathway further as elevated CO_2 favors C_3 pathway so it is better to estimate C_3 weeds (*P. minor*, *R. dentatus*, *C. album*) with C_3 crop (wheat). The elevated CO_2 condition favors C_3 plant photosynthetically mechanism whether it is a crop or weed, but the competitiveness of crop against weeds will be fluctuates and bounded by the availability of resources.

However, most of studies advocated that crop weed interaction (C_3-C_3) differs significantly under raised CO_2 environment and favors C_3 weed flora under limited nutrient, water availability conditions (Valerio et al. 2011; Zhu et al. 2008). Climate change bound to influence the ecology of weeds with possible implications for their management. Due to greater genetic diversity in weeds these can better adapt to the changing climate as compared to crops. Management of weeds is likely to become more difficult in future because of grater invasiveness, weed shifts and development of herbicides resistance under changing climate. Further, weed flora may shift crop-weed completion and subsequent yield losses in crops under these conditions. Oraki et al. (2016) reported increase in wheat yield loss due to competition with *Avena Ludoviciana* L. (100 plants m^{-2}) from 76.5% to 88.8% with rise in CO_2 concentrations (400–1000 ppm). The yield losses increased significantly in wheat due to *Phalaris minor, Avena sterilis*, *Galium tricornatum* and *Sinapis arevensis* at elevated CO_2 concentrations (750–800 ppm) as compared to ambient (500 ppm). Further, alone *S. arvensis* reduced wheat by 50% at ambient but 95% at elevated scenario (Mese and Dogan 2015). Sarathambal et al. (2016) revealed elevated CO_2 increased diacetate hydrolysis rate and urease activity in wild oat, while higher dehydrogenase activity in *P. minor* as compared to wheat in rhizosphere. Elevated CO_2 concentration C_3 plants are likely to become more water-efficient and potentially allow C_3 weeds to move into drier parts. CO_2 increased wild oat dry weight by 34% and produced 44% more seed at 480 ppm as compared to 357 ppm (O'Donnell and Adkins 2001). Further, CO_2 enrichment hastened seed maturity in *Avena fatua*as seeds matured 13 days earlier than to plants grown in ambient CO_2 conditions (Naidu 2015). The rise in temperature (4 °C) under ambient conditions, weight of seeds and biomass decreased by 14.6% and 47.3%, respectively, but when same scenario superimposed with elevated CO_2increased above variables by 114.4% and 33.9%, respectively as compared to controlling *C. album* (Lee 2011). But, the effect of increased temperature on biomass accumulation was more pronounced during reproductive stage as compared to vegetative in C_3 crops and likely to counteract potential benefits of increased CO_2 by restricting reproductive output. Biomass and leaf area response also found in the range (1–1.5, 1.22); (1.18, 0.96) and (0.95–1.6, 0.98–1.77) under CO_2 fertilization compared to ambient for *Chenopodium album*; *Rumex Crispus* and *Echinochloa crusgalli*, respectively (Patterson 1995; Chandrasena 2009; Streck 2005). Under water stress conditions, wheat gained more biomass than *P. minor* and showed more competitive ability; however, *P. minor* showed advantage over wheat under CO_2 enrichment (Naidu and Varshney 2010). Alberto et al. (1996) suggested that rice crop (C_3) competitiveness could be enhanced relative to C_4 *Echinochloa glabrescens* weed under CO_2 enrichment but concurrent increased CO_2 and temperature still favor *Echinochloa glabrescens.* Under optimum supply of nitrogen and elevated CO_2, relative proportion of rice (C_3) biomass increased as compared to *Echinochloa crusgalli* (C_4). But in limited nitrogen scenario weeds compete effectively with C_3 crops may offset optimistic positive response in rice yield under future CO_2 fertilization (Zhu et al. 2008). Thereby, important climatic variables (rise in atmospheric CO_2, temperature and deficit moisture in soil profile) are likely to be influenced population dynamics of weed species, crop weed interaction and determine their future gravity of infestation.

20.8.2 Herbicide Efficacy

Herbicides efficacy and management practices employed to control weed species arelikely to be affected under elevated CO_2 and temperature. Elevated CO_2 affect herbicides uptake and translocation in plants associated with anatomical and morpho-physiological changes in plants (Manea et al. 2011; Ramesh et al. 2017). Efficacy of foliar and soil active herbicides are likely to be reduced under elevated CO_2 conditions due to reduction in stomata number, conductance and transpiration while, cuticle thickness increases with more starch accumulation on the plant surface (Ainsworth and Long 2005; Patterson 1995; Bailey 2004). Differential uptake, translocation and metabolism of the herbicide at biochemical level decide the fate of resistance development in weeds. Vigrous vegetative growth with greater photosynthetic rate under elevated CO_2 resulted in higher allocation of photosynthates to below ground parts in perennial weeds (Ziska 2016). This could give "dilution effect" on applied systemic herbicides with greater conjugation of active chemicals and likely to cause significant problem of perennial weeds in no till conditions. Furthermore, due to decrease in protein content in plant tissue along with lower requirement of amino acids could affect efficacy of amino acids/protein synthesis inhibitor [ALS/AHAS, shikimate acid (EPSP) pathway (glyphosate), glufosinate] under elevated CO_2 (Bowes 1996). The incidences of non-target site or metabolic based herbicide resistance are also likely to be higher in near future (Matzrafi et al. 2016). So in near future problem of weeds (*Phalaris minor*, *Avena ludoviciana*, *Rumex dentatus* Linn, *Chenopodium album* and *Polypogon monspeliensis*) due to their C_3 mechanism along with greater plasticity likely to reduced wheat yield more and may offsets CO_2 fertilization effect in wheat especially during resources limited scenario.

20.9 Future Perspectives

There is need to exploit maximum weed seed depletion through utilizing seed predators, tillage manipulations and seed destructor technologies such as Harrington Seed Destructor for effective seed predation, congenial habitat consisting of no-tillage and residue retention along with reduced pesticide usage should be provided to the seed predators. Also the effective integration of false seed bed technique can help in reducing the soil weed seed bank.

The sole dependence on single herbicide for controlling weeds has responsible for the evolution of herbicide resistance in weeds as well as the shift in weed flora. Therefore, future studies need to be directed towards integration and evaluation of the compatibility/suitability between different grass and or broad-leaved herbicides. Also, the use of herbicides in rotation, sequence and mixture can help in delaying and managing the herbicide resistance evolution. Wherever the compatibility issue is there focus should be on the sequential usage of herbicides consisting of pre-emergence herbicides followed by either early post or post-emergence herbicidesto reduce the selection pressure thereby delaying the chances of herbicide resistance evolution in weeds.

The actual mechanism of resistance in many weeds along with fitness or competitiveness of resistant biotypes compared to that of normal susceptible biotypes is not fully understood. So there is need to investigate these aspects systematically to check further proliferation of herbicide resistance.

Sole dependence on herbicides along with mono-cropping sequence leads to the shift towards hard to control weeds and the rapid development of herbicide resistance, which could threaten the crop productivity. There is need to advocate suitable wheat based crop rotations and alternate herbicidal options for management of herbicide resistance so that the problem of herbicide resistance can be undertaken effectively. More alternative herbicides should be used in rotations and mixtures, as using different mechanisms of action have pronounced effect in delaying the appearance of resistance. Even, proper advisory should be given with rotation of low risk herbicide with high risk herbicide during recommendation and introduction of new chemical.

The long-term effective herbicide resistance management strategies should be planned with the integration of herbicidal and other crop management based approaches such as crop geometry, timely sowing, adoption of suitable tillage practices, avoid burning of crop residue rather retaining to restrict weed emergence and multiplication of seed predator along with ecology and biology of weed.

Concerted efforts are also required for developing crop cultivars having strong weed suppressive effects during the initial crop stages. This will be the first step towards weed management through crop competition. In addition, determination of specific means of improving crop competitiveness, through altering crop genetics and agronomic practices, are required. Integration of improved crop cultivars and crop management practices will help in maximing crop interference to suppress weds and increase crop yields.

Through improved agronomic practices, crop/weed interactions should be exploited to shift weed-crop competition favouring the crop. Improved agronomic practices which can favour the crop over weeds by providing an early-season competitiveness are closer row spacing, increased seeding rates, altered row orientation, competitive varieties. These practices besides maximizing the resource utilization by the crop will reduce weed growth and seed bank additions. These ecological weed management strategies require appropriate integration for the potential benefits of reduced dependence on herbicides. Moreover, the cropping system diversification approach involving crop rotation and intercropping will help in devising substantial weed management strategies.

20.10 Conclusions

Weeds are the major constraint in wheat and barley production. Weeds compete for growth resources such as nutrient, water, light and space thereby reducing wheat yield by 4–40% and even more in herbicide resistance dominated regions. On global scale, herbicide resistant screened out at more than 35 countries more against ACCase and ALS based inhibitors as compared to PSII and synthetic auxins in wheat and barley growing regions. Tillage and cropping system acts as filter and increase weed diversity more under no till and diverse crop rotation. Sole reliance on herbicides needs to be discouraged rather integration of different measures such as stale seed bed, zero tillage, diverse crop rotation, cover crops and mulching, competitive cultivars and cultivars blending, higher crop seed rate, narrow spacing, row orientation, early seeding, band placement/point injection of fertilizers is required. Irreversible loss in weed seed can be improved by enhancing weed seed predation and adoption of weed seed-based destructor. Problem of weeds under conservation-based system is likely due to absence of tillage support, more weed diversity and poor efficacy of soil active based herbicides. Further, increase in temperature and atmospheric CO_2 is likely to increase the frequency of target and metabolic inhibitor-based resistance in weed species.

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Agroforestry for Sustainable Cereal Based Cropping Systems in Indo-Gangetic Plain Region

21

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21.1 Introduction

Indo-Gangetic plains (IGPs) are the catchment area of rivers namely Indus and Ganga covering Indian states of Punjab, Haryana, Rajasthan, Gujarat, Uttar Pradesh, Bihar and West Bengal. IGPs cover almost 700,000 km^2 and being most populous area, it acts as a home for 1/seventh of the World population (Tiwari et al. 2016). It covers around 15.3% of India's geographical area but contributing about 50% of total food grain production, so also known as 'food bowl' of India. Continuous sedimentation of fertile soil from Himalaya has made IGPs the most fertile area of the world. IGPR represents eight agro-ecological regions and 14 agro-ecological sub-regions and supporting 33% human and 35% livestock population of India (Pathak et al. 2014).

Overall, the region has a mixed economy with good growth of agriculture, horticulture, and animal husbandry. The major cropping systems are rice-wheat, maize-wheat, sugarcane- wheat, cotton-wheat, rice-mustard-jute, rice-potato and rice-vegetables-jute (Koshal 2014). But predominated system is rice-wheat and occupies about 72% of the total cultivated area of the region. Better adaptability of this cropping system among farmers is attributed to high yield potential, availability

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of high yielding varieties and mechanization of both crops, suitable agro-climatic conditions etc. (Ram et al. 2016). On the basis of cropping pattern, this region can further be divided into two major zones viz., western (Haryana, Punjab, parts of central, western & northern U.P. dominated by rice-wheat cropping system) eastern zone (Eastern UP, Bihar and West Bengal dominated by rice based cropping system). After green revolution, farmers are regularly practicing these cropping patterns without any diversified landuse pattern which resulted into emergence of sustainability threatening challenges in the agriculture.

21.2 Problems and Challenges for Sustaining Agriculture in IGPR

Although Indo-Gangetic plains Region is major contributor toward self-sufficiency of India in food grain production but after decades of continuous mono-cropping systems, over irrigation, urbanization, pest pressure, imbalance use of nutrients, burning of crop residue and water shortage (Koshal 2014), the agroecosystem of IGPR depleted very deleteriously (Panwar et al. 2017). Substantial deterioration of soil and environment health due to excessive use of inorganic farm inputs particularly fertilizers and pesticides, lowering of water table and high rate of environmental pollution are the matter of concern for sustainability of the Indo-gangetic plain region. There has been tremendous increase in production area and productivity of food grains, which however, has not come without negative impact on ecology, thus, affecting the generations to come. The mankind is facing a huge challenge of meeting its basic needs of food, shelter, etc. on the one hand and conservation of natural resource on the other hand. The use of agrochemicals in agriculture crop production promised food security, but at the cost of polluting air, soil and water resources. The loss of forest land, for human habitation, developmental activities and intensive agriculture resulted in ecological imbalance (Chauhan 2012). There is a dire need to rehabilitate the soil health and maintain water resources to develop a suitable sustainable land use system. As agriculture continues to be the basic life supporting system in this state (84% area of the state is cultivated), attempts, therefore, would be required to tackle the major land issues first.

21.2.1 Climate Change and Impact on Agriculture

Agriculture is the major livelihood option for over 60% of Indian rural households (FAO 2017) and world largest industry with major land use and global spread on approx. 40% available land. Agriculture in South Asia and India is vulnerable to climate change. Variability in Climate explains around 60% variation in yield and thus remains a crucial factor for food production and income at farm level (Osborne and Wheeler 2013; Ray et al. 2015; Matiu et al. 2017; Aryal et al. 2020). Presently IGPR experiences relatively low temperatures. But extreme high temperature events and rainfall intensity days will be more frequent due to climate change effect. Rabi season crop such as Wheat and Barley requires low temperature for higher growth and development but increase in temperature will affect the growth of these crops. The projected changes in climatic conditions are likely to reduce the productivity of rice-wheat cropping systems in IGPR. The extreme temperature in rabi season will cause the reduction in crop duration, grain number and grain filling duration.

21.2.2 Declining Underground Water Table and Water Pollution

Rice-Wheat cropping system consumes about 11,650 m^3 ha^{-1} water out of which rice consumes around 66 per cent and 34 per cent by wheat. Further, with climate change and non-judicious use, ground water is depleting in the IGP region. Besides, a current annual water deficit of around 1.27 M ha-m (Jain and Kumar 2007) owing to escalated water demand (Minhas et al. 2010), there is a need to address the issues relating sustainable crop production and rational use of water. Further, excessive use of fertilizers and other plant protection measures, in IGP region has polluted the water quality. Nitrogen fertilizers results in leaching of nitrates and further pollution of ground water. This polluted water is very harmful for human as well animals' health.

21.2.3 Diverse Weed Flora

With intensive agriculture, mainly rice-wheat sequence in IGP region and change in establishment methods (if not adopted properly) yield has been adversely affected. Direct seed rice is advocated to have higher productivity, but diverse weed composition and chances of yield losses are higher (Chauhan et al. 2012a; Forcella 2003; Chauhan and Johnson 2010). Also, over the last decade new breeds of insects-pest/diseases have appeared which are responsible for the stagnating/lowered land productivity.

21.2.4 Crop Burning

Burning of residue crop is being practices in the major states of IGP, states of Haryana, Punjab, and Uttar Pradesh with an aim to clear the fields for *rabi* crop sowing. Because the time window available between the harvesting of paddy crop and sowing of next crop is very short (15–20 days). The poor air quality in the NCR region, especially during winter months (Oct–Nov) is a matter of concern and a direct cause of this pollution.

There is an increasing trend of harvesting of rice and wheat through combine, which is less laborious, more time efficient but leading to the production of an enormous quantity of crop resides (especially rice residues). In Punjab, more than 40% rice and wheat residues are burned in situ annually, leading to approx. five million Mg C loss (Benbi et al. 2011). One Mg of wheat reside contains 4.8 kg N, 0.7

P and 9.8 kg K, whereas, 1 Mg of rice residue contains 6.1 kg N, 0.8 kg P and 11.4 kg K. Burring of rice straw caused gaseous emission of 70% CO, 0.66% CH4 and 2.09% N2O and loss of 80% N, 25% P, 21% K and 4–60% S (Lefroy et al. 1994; Bhattacharyya et al. 2016). Thus, brining of crop residue threaten the health of both human and ecosystem. The state government and Govt of India has taken steps like, notification banning burning of crop residue, imposing fine, promoting in-situ crop residue management, agricultural mechanization including subsidy programs, etc. But there is very less hope for a permanent alternate or a solution.

21.2.5 Soil Physical and Chemical Degradation

Unbalanced fertilizer uses and use of only mineral fertilizers depletes SOM and plant nutrients, mainly N. Excessive tillage, formation of new beds (for vegetable cultivation) every season and use of heavy machinery cause soil physical degradation. Repeated cultivation for wheat and/or soil physical problems caused by puddling of soil for rice further adds to soil degradation. Important among physical processes are a decline in soil structure leading to crusting and compaction. In intensively cultivated soils, repeated use of heavy farm machinery for tillage and other operations often results in compaction throughout the plough layer. This is more rampant in the rice –wheat systems, where puddling is done for rice followed by several tiller and disc harrow passes for wheat cultivation. Several studies have revealed that puddling increased soil bulk density (BD; >1.60 Mg m $-$ 3) in the sub-surface layer (15–30 cm) in rice-based systems (Chauhan et al. 2012a), (Kumar et al. 2010) (Rodell et al. 2009). An increase in BD invariably increases penetration resistance (PR) and obstructs root development. Critical values that severely restrict root growth have been estimated to vary from 1 to 4 MPa depending on the soil, water content and crop.

21.2.6 Problematic Soils

Healthy Soils are one of the major contributors to increased productivity and income but often ignored as major emphasis is always given on improving package and practices of crops /systems. Main reasons of land degradation in IGP are erosion by water, residue burning, depletion of nutrients, poor water management-poor management of canals irrigation, unsustainable cropping systems, water erosion in few areas, and potential effects of climate change.

21.2.7 Labour Shortage

Rice-wheat cropping system is water-energy-capital and most importantly labour intensive as all the operations from field preparation to harvesting & storage requires intense labour. Mechanization like, mechanical transplanting (Bhatt and Kukal

2015) and direct seeded rice (Bhatt and Kukal 2015) are the reliable options as manual is labour intensive. However, there is a higher weed in mechanical transplanting under Zero tillage, which further requires labour. Labour scarcity has increased in agriculture as assured working days are offered in MANREGA scheme of Government. Several reports (Kamboj et al. 2013) considered labour shortage as the hurdle towards sustainable agriculture.

21.2.8 Minimum Support Prices (MSP) and its Implementation

The MSP is a minimum price guarantees that acts as a safely net or insurance for farmers when they sell crops. MSP set by the Central government for selected crops, based on recommendations from Commission for Agricultural Costs and Prices (CACP). Govt to improve farmers income, made few amendments and brought three bills in the year 2020. The Farmers Produce Trade and Commerce (Promotion and Facilitation) Bill, 2020 which help farmers to sell their produce outside APMC mandis even outside their own state, based on higher prices they get. The farmers (Empowerment and Protection) agreement on Price assurance and farm services bill, 2020- allow farmers to enter a contract farming at a pre-approved price. Third, bill is the Essential commodities (amendment) bill which declassified items, like onion, cereals, pulses, potatoes, edible oilseeds, and oil as essential items in normal circumstances. Existing mandi structure is already leading to exploitation of farmers by middlemen but introducing them to bigger players could harm them even more. Policy makers are quite hopeful that implementation of this bill will provide farmers remunerative price for their produce.

21.3 Potential of Agroforestry in Sustaining Agriculture

Agroforestry is neither new nor unique for us, it is practiced successfully in India from age old. Agroforestry is a landuse management system that promote cultivation of agricultural crops, variety of trees, shrubs, herbs and also provides several ecosystem services such as improvement in soil fertility, water cycle regulation, carbon sequestration etc. ‘Sustainability’ was a way of life. If we bring back this practice to our farmers, we can spark a new revolution in the agricultural sector and the Indian economy. India is a first country in world which come out with Rally for Rivers, launched by Sadhguru, founder of Isha Foundation, in 2017, and recommended by Niti Aayog for implementation across India, offers a well-defined roadmap for farmers to successfully switch partially to agroforestry to address the multiple challenges they face. These include deteriorating soil quality, inadequate water resources, untenable irrigation practices, poor quality crop, fluctuating markets and crippling debt.

The natural forest resources in IGPs ranges from 0.86% (Haryana) to 13.50% (West Bengal) and on an average 7.72% of the total geographical area (FSI, 2019). The average number of trees in IGPR in Rainfed conditions is 15–33 trees ha^{-1}

which increases to 10–500 trees under areas with irrigated conditions (Dagar et al. 2014). In rainfed areas, scattered trees and in irrigated areas high density plantation are the common practice of agroforestry in Indo-gangetic plains. In Trans IGPs, *Populus deltoides*, *Eucalyptus* spp., *A. indica*, *Dalbergia sissoo* are common species that are kept under agrisilviculture system. Horticulture based agro-forestry is followed mostly in all over IGPs with more prevalence in lower and middle IGPs with major fruit species viz. Mango (*Mangifera indica*), Guava (*Psidium guajava*), Jamun (*Syzygium cuminii*), Bael (*A. marmelos*), Litchi (*Litchi chinensis*), Jack fruit (*A. heterophyllus*), *Citrus* spp., Papaya (*C. papaya*), Banana (*Musa paradisiaca*), Amla (*Emblica officinalis*), Ber (*Zizyphus mauritiana*), Mango (*Mangifera indica*) and Sehtoot/Mulberry (*Morus alba*). Traditionally agroforestry has been practices in IGPs by keeping local and indigenous species on farm for fulfilling need of fruits, fuel, timber, medicinal usage, fodder etc. Traditional agro-forestry practices in Indo-gangetic plains includes following:

21.3.1 Scattered Trees on Farm Land

This practices is followed since ages in IGPs and in both rain-fed as well as irrigated conditions and 10–50 trees/ha are generally kept on farmland. These trees serve purpose of providing fodder for livestock, fuel-wood for household, medicines for local usage, fruits for human consumption and wood for making agricultural implements and local timber usage. The tree species that are kept on farm varies from region to region and mostly includes *A. marmelos, A. lebbeck, A. catechu, A. nilotica, Ailanthus excelsa*, *A. indica, Anogeissus laitfolia, B. variegata*, *B. monosperma, Dalbergia sissoo, Emblica officinalis, Grewia optiva, Litchi chinensis, Mangifera indica, Melia azedarach, Morus alba, Prosopis cineraria*, *Syzygium cuminii, Ziziphus mauritiana* and many aforementioned fruit trees (Pathak et al. 2014).

21.3.2 Trees on Farm Boundaries

This type of agroforestry is prominent in Bihar, Haryana and Punjab and tree species like *Dalbergia sissoo*, *Eucalyptus spp.* and *Populus deltoides* are commonly grown along the field boundaries in Haryana and Punjab, while *Dalbergia latifolia* and *Wendlandia exserta* are grown in Bihar. In Haryana and Punjab where water logging is common *Eucalyptus spp.* and *Populus deltoides* have been planted along field boundaries as bio-drainage species to reduce negative impact of the excessive water on field crops (Handa et al. 2019; Ram et al. 2016).

21.3.3 Traditional Home Gardens

In Eastern Uttar Pradesh, Bihar and West Bengal growing of multiple tree species around home forming multi-strata are common among small and marginal farmers. In West Bengal, Banana, Coconut and Areca nut are grown (Panwar et al. 2017), while in eastern Uttar Pradesh, Jackfruit, Neem, Bamboos, Guava, Banana and *Citrus* spp. are grown by the farmers (Rana et al. 2007); In Bihar, Mango, Litchi, Banana, Papaya and Shisham trees are grown (Chaturvedi 2001; Chaturvedi and Das 2007).

21.3.4 Traditional Silvopastoral Systems

In IGPs, local fodder trees are being grown since ages on local grazing lands for feeding livestock during lean period (Table 21.1). Depending upon the climatic conditions of fodder trees such as *A. latifolia, B. variegata, C. australis, Ficus spp., Grewia optiva, Morus spp. Terminalia bellirica, Ziziphus nummularia, Ziziphus mauritiana* are widely grown for feeding livestock (Pathak et al. 2014). Besides this traditionally agrisilvi-pasture comprising of growing fodder trees on bunds and boundaries of farmland are also practised to ensure nutritious green fodder during lean period for livestock (Pathak and Roy 1993; Sarlach et al. 2007; Chaturvedi and Das 2007). Prevailing agroforestry systems and preferred species in different states under Indo-gangetic plains in depicted in Table 21.2.

Table 21.1 Preferred multi-purpose tree species and crops under various zones of Indo-Gangetic plains

Region	Preferred tree species	Preferred Crops
Lower Gangetic plains region	*Eucalyptus hybrid, A. auriculiformis, Gmelina arborea, A. nilotica, A. indica, A. lebbeck, Litch chinensis, Psidium guajava, Delbergia sissoo*	*Oryza sativa, Triticum aestivum, Colocasia spp., Sorghum bicolor*
Middle Gangetic plains region	*Populus deltoids, A. cadamba, Eucalyptus hybrid, Dalbergia sissoo, A. nilotica, bamboo, Mangifera indica,*	*Oryza sativa, Triticum aestivum, tuber crops, vegetables and medicinal plants*
Upper Gangetic plains region	*Populus deltoids, Eucalyptus hybrid, Dalbergia sissoo, A. cadamba, Leucaena leucocephala, Psidium guajava*	*Oryza sativa, Triticum aestivum, Pennisetum glaucum*
Trans-Gangetic plains region	*Populus deltoids, Eucalyptus hybrid, Dalbergia sissoo, Melia azedarach, A. nilotica*	*Triticum aestivum, Oryza sativa, Vigna mungo, Vigna radiata*

Source: (Planning 2001)

Table 21.2 Prevailing agroforestry systems and preferred species in different states under Indo-gangetic plains

Region	Agroforestry System	Multipurpose tree species preferred	Agricultural crop grown
Punjab	Agri-silviculture	*A. nilotica, Dalbergia sissoo, A. catechu, Ziziphus sp., B. monosperma, Grewia optiva*	Pearl, millet, Sorghum, Sunflower, sugarcane
	Farm boundary	*Populus deltoids, Eucalyptus spp.*	Rice, wheat, cotton, potato
Haryana	Agri-silviculture	*Populus deltoides*	Rice, wheat, potato, Sunflower, sugarcane
	Agri-horticulture	*Mango, Citrus Litchi,* Ber	Rice, wheat, potato, Sunflower, sugarcane
	Farm boundary	*Eucalyptus hybrid, Populus deltoides*	Rice, wheat, potato, Sunflower, sugarcane
	Scattered trees	*Prosopis cineraria, A. nilotica, A. tortilis, Dalbergia sissoo*	Pearl, millet, Sorghum, sunflower
Western Uttar Pradesh	Agri-silviculture	*A. indica, Dalbergia sissoo, A. nilotica* Mango	Rice, wheat
	Horti-silviculture	*Populus deltoides, Mangifera indica, Emblica officinalis, Psidium guajava, A. marmelos*	
	Block plantation	*Eucalyptus hybrid, Populus deltoides*	
	Farm boundary	*Eucalyptus hybrid, Populus deltoides*	
Central Uttar Pradesh	Agri-silviculture	*A. indica, Dalbergia sissoo, Mangifera indica, Psidium guajava, Zizyphus mauratiana, A. lebbeck*	Rice, wheat
	Farm boundary	*A. nilotica, Prosopis juliflora, Eucalyptus spp, Ficus religiosa, A. catechu, Madhuca latifolia,* bamboo *spp.*	
Eastern Uttar Pradesh	Agri-horti-silviculture	*Dalbergia sissoo*, mango, guava	Vegetables, wheat
	Farm boundary	*Dalbergia sissoo, Eucalyptus sp.*	Rice, wheat
	Homestead	*Madhuca latifolia, Dalbergia sissoo, A. indica,* bamboo, *Syzygium Cuminii, Ficus sp.* Mango, guava	Vegetables, wheat, ginger, turmeric
North Western Bihar	Agri-silviculture	*Dalbergia sissoo, B. ceiba, Tectona grandis, Ziziphus jujuba*	Wheat, maize, Paddy
	Agri-horti-silviculture	*Morus alba, Terminalia arjuna, Mangifera indica, Litchi chinensis, Emblica officinalis*	Wheat, maize, Paddy
	Silvi-agriculture	*C. fistula, B. ceiba*	Wheat, maize, Paddy

(continued)

Table 21.2 (continued)

Region	Agroforestry System	Multipurpose tree species preferred	Agricultural crop grown
	Homestead	*A. indica, Dalbergia sissoo,* mango, jackfruit, Litchi, guava, *Emblica officinalis*	Ginger, turmeric
	Silvi-pastoral	*Dalbergia sissoo, A. nilotica*	Maize (fodder), local grass
	Farm boundary	*Dalbergia sissoo, Wendanlandia exerta*	Wheat, gram, Rajmah, Castor
	Shelter belt	*Dalbergia sissoo, Dendrocalamus strictus*	Wheat, maize, Paddy
West Bengal	Homestead	*A. indica, Dalbergia sissoo, Leucaena leucocephala,* mango, Jackfruit,Guava, Bael, Ber	Vegetables, ginger, turmeric
		A. nilotica, Terminalia arjuna, A. indica, B. monosperma, Ziziphus mauratiana	Rice, red gram, black gram, moong bean, mustard, maize, Sunhemp

Source: Planning commission (2000)

21.4 Prominent Agroforestry System in IGPR

21.4.1 Poplar Based Agroforestry Systems

Populus deltoides is a mostly preferred and a dominant agroforestry tree species (Table 21.3) grown by farmers in IGPs owing to its short rotation, compatibility with agricultural crops and high demand in wood-based industries, deciduous nature and high profitability. *Populus deltoides* is grown as block plantation, alley cropping and boundary plantations in IGPs covering states of Punjab, Haryana, and Uttar Pradesh and rotation age is fixed between 6–9 years based on demand for size of wood (Panwar et al. 2017). It is estimated that this wood is source of raw material for matchbox, veneer, packaging, plywood, pulpwood and paper industries.

Most appropriate spacing for growing *Populus deltoides* is 5 × 5 m but farmers have been observed to prefer 5 × 4 m spacing just to accommodate more number of trees (Gandhi and Dhiman 2010). Most preferred crop under poplar is wheat as it is winter crop and that time poplar undergoes leaf fall (October onwards till February) and its new leaves starts appearing during end of the March. During initial year there is no reduction in the yield of wheat crop but as the age of trees increases 10–46% loss in the yield has been observed (Gill et al. 2009). Competition for below and above ground resources often changes with the increase in tree age, however the overall system yield increases towards the end of the poplar rotation age (Chauhan and Johnson 2010); (Chauhan et al. 2015). For first 3 years, any *rabi* and *kharif* crop (except paddy) of the region can be grown under poplar, and thereafter on third year barley (*Hordeum vulgare*), berseem (*Trifolium alexandrinum*), cabbage (*B. oleracea var. capitata*), chilly (*Capsicum acuminatum, C. annuum*), coriander (*C. sativum*),

Table 21.3 Performance of different agricultural crops under Poplar based agroforestry

Tree	Tree spacing	Crops	Yield	Economics BC Ratio	References
Populus deltoides 7 year old	5 × 4	Wheat (Var. HD-2967)	2.10 t/ha	–	Sirohi et al. (2016)
	10 × 2		2.80 t/ha		
	18 × 2 × 2 (paired row)		3.00 t/ha		
Populus deltoides 5 year old	5 × 4 m	Fennel Var. FH-33 Seed yield	0.31 t/ha	1:1.27	Rathee (2017)
	10 × 2 m		0.39 t/ha	1:1.33	
	18 × 2 × 2 m (paired row)		0.62 t/ha	1:1.66	
Populus deltoides 5 year old	5 × 4 m	Ajwayan Var. local Seed yield	0.15 t/ha	1:1.10	
	10 × 2 m		0.22 t/ha	1:1.20	
	18 × 2 × 2 m (paired row)		0.31 t/ha	1:1.32	
Populus deltoides 4 year old	4.5 × 4.5 m	Wheat Var. PBW-343	1.7 t/ha	–	Chauhan et al. (2012b)
Populus deltoides 5–6 Year old	8 × 2.5 m	Potato Var. Pukhraj	26.3 t/ha	–	Singh et al. (2019)
Populus deltoides 5 Year old	8 × 3 m	*C. flexuosus*	Herbage: 43.20 t/ha Essential oil: 175.40 kg/ha	–	Raj et al. (2010)
Populus deltoides 4 year old	8 × 2.5 m	Turmeric Variety: PH-42	Processed rhizome yield: 21.1 q ha Curcumin yield: 95.37 kg ha $^{-1}$ yield	–	Bijakal et al. (2019)

ginger (*Zingiber officinale*), mustard (*B. juncea. B.oleracea, B.nigra*), oats (*A. sativa*), strawberry (*Fragaria chiloensis*), tomato (*Lycopersicon esculentum*), turmeric (*C. domestica*), colocasia, potato, spinach, garlic including fruit crops (citrus, guava, mango, wheat (*Triticum aestivum*) etc. can be grown till rotation age of poplar. Sugarcane (*Saccharum officinarum*) inter-cultivation for initial 2 years has also been found more profitable (Sharma 1996).

Poplar after 8 year of rotation age has been reported to give 150–200 m^3 ha^{-1} yield of wood under block plantation and 12–20 m^3 ha^{-1} under boundary plantation (Pathak et al. 2014) and spacing of 5 × 4 m recommended for good performance of Poplar tree under agri-silviculture system (Lal 2004). The total above ground biomass yield of Poplar trees under Indo-Gangetic plains has been found to be ranging from 7.4 t ha^{-1} (one year age) to 105.4 t ha^{-1} (10 year age) under block plantation (Pathak et al. 2014).

The financial and economic analyses of 8 year rotation based Polar based agroforestry on growing it on bunds has been reported to provide net present value were ₹137,000, ₹127,000 and ₹118,000 at various discount factors (8%, 10% and 12%, respectively) and Benefit: Cost Ratio of 2.8 under aforementioned discount factors. Under 8 year rotation based Polpar-agri-silviculture, net present value was found to be ₹123,000 ₹111,000 and ₹ 101,000, respectively for 8,10 & 12% discount factors and Benefit cost ratio (BCR) of 2.18, 2.15 and 2.12 was observed which is quite higher than BCR (1.34 to 1.42) of traditional cropping system (Kareemulla et al. 2005). One study carried out on agroforestry system with 10 × 2 m spaced poplar tree and sorghum-berseem crop rotation; net returns of ₹1,191,241 ha^{-1}, net present value of ₹ 409,673 ha^{-1} at 12% discount rate; BCR of 1:2.22 and IRR of 70%, highest land equivalent ratio of 2.28 and land expectation value of ₹ 2,242,372 ha^{-1} has been obtained (Chavan and Dhillon 2019). This indicates that Poplar based agroforestry is more remunerative than traditional cropping pattern.

21.4.2 Eucalyptus Based Agroforestry Systems

Eucalyptus teriticornis is grown in Indo-gangetic plains in states of Haryana, Punjab and Uttar Pradesh for meeting out demand of plywood, pulpwood, paper and timber firms. For pulpwood rotation is kept as 5 years and for timber it is generally kept as 8 years (Pathak et al. 2014). It is grown on farm bunds, as block plantations, along canals and road. Many crops like *Capsicum* spp. (chilly), *Vigna mungo* (blackgram), *Vigna radiata* (greengram), *Oryza sativa* (Rice), *Gossypium arboretum* (cotton) *A. hypogaea* (ground nut), wheat, potato, mustard, lentils and *Trifolium alexandrinum* (Barseem) can be intercropped successfully under *Eucalyptus* intercrops during the very first year of planting ((Pathak et al. 2014); (Ahlawat et al. 2019). These crops can also be grown in the second and third years but then, it can lead up to 70% yield losses in intercrops). *Eucalyptus*-wheat-based agroforestry is the most commonly practiced in Indo-Gangetic Plains under the irrigated or waterlogged conditions. Under *Eucalyptus*–wheat-based agroforestry, during *kharif* season fodder crops like sorghum and pearl millet can be grown for initial 4 years (Dagar et al. 2016a). *Eucalyptus* trees raised from seedlings can produces about 20–25 m^3 ha^{-1} yr.$^{-1}$ under un-irrigated conditions and in case of clones up to 50 m^3 ha^{-1} yr.$^{-1}$ under plantations (Pathak et al. 2014). If irrigation facilities are available then farmers of Punjab and Haryana have witnessed 200 tones biomass production from *Eucalyptus* with net returns of one million Indian rupees ha^{-1} at 10 years rotation age (Lal 2004).

E. tereticornis planted at 3 × 2 m spacing has been reported to impact wheat grain yield in the vicinity of its trees up to 2 m (114 g/m^{-2}) which increased to 379 g/m^{-2} at 6 m distance from tree and tree biomass of about 28.77 kg tree^{-1} and 0.0215 m^3 tree^{-1} (volume) has been obtained after 4 year of establishment (Tripathi et al. 2019).

An experiment carried out in Punjab by planting *Eucalyptus* at 6 × 3.5 m with intercropping of turmeric (annual) has provided maximum net returns of rupees

14,62,065/ha after 6 years (Kaur et al. 2017). Turmeric gave 21.7 t/ha rhizomes yield in the first year of intercropping which decreased to 12.2 t /ha in the sixth year (Kaur et al. 2017). When potato was grown under *Eucalyptus* (6 × 3.5 m-spacing) in Punjab conditions, maximum yield was obtained during first year of establishment i.e. 21.9 t/ha which decreased to 13.4 t/ha during sixth year of establishment (Kaur et al. 2017).

Eucalyptus (3.9 × 1.5 m spacing) when intercropped with mustard and oat resulted in 1.52 t/ha and 5.50 t /ha yield respectively during first year of establishment which decreased to 1.30 t/ha and 4.94 t/ha respectively during second year (Ahlawat et al. 2019). The net returns from mustard and oat were Rs 6067/ha and Rs 26,535/ha respectively during first year and Rs 6889/ha and Rs 14,580/ha respectively during second year (Ahlawat et al. 2019). But with the increment in *Eucalyptus* trees the total system yield will increase towards rotation age and will enhance farm returns as merchantable stem of *Eucalyptus* trees can be sold @ Rs 5500–6000/t. This indicates *Eucalyptus* that based agroforestry is also remunerative than traditional cropping pattern.

21.4.3 *Dalbergia sissoo* and *Melia composita* Based Agroforestry Systems

Indigenous tree species like shisham *(Dalbergia sissoo* Roxb.ex DC) and *Melia composita* are also being grown under agro-forestry in IGPs. *Dalbergia sissoo* can also be integrated successfully with *Oryza sativa* and *Triticum aestivum* under IGPs (AICRP-AF 2016). Moreover, *Dalbergia sissoo* has also been found compatible with mustard, gram, aloe-vera and many other medicinal crops. *Dalbergia sissoo* wood possess good strength, durability, elasticity, wood grain and colour therefore is highly demanded for making furniture, musical instruments, sports equipments, boats etc. It is usually planted in Punjab, Haryana and Uttar Pradesh on field bunds and as scattered trees under agri-silvicullture systems. *Melia composita* is very fast growing tree species with huge demand in pulp, paper, and plywood industries. It has been found compatible with wheat, turmeric, potato, Egyptian clover and Pearlmillet under spacing of 6 m × 3.5 in IGPs (Kaur et al. 2017). Merchantable stem of *Melia composita* fetch a good price of Rs 6000/t in market. Moreover, like Poplar, *Melia composita* is winter deciduous tree species therefore; better performance of agriculture crops has been observed under it than other tree species. Besides this, *Melia composita* has been found suitable for saline soil agroforestry and mustard as well as Pearlmillet can be grown with this tree species under saline soils (Banyal et al. 2018).

21.5 Agroforestry for Degraded Land Reclamation in Indo-Gangetic Plains

In Indo-Gangetic plains, agroforestry can play a major role in the rehabilitation of lands degraded by salinization, soil erosion and water logging. Following trees, crops and agrorofrestry models have been found suitable for reclamation of various types of problematic soils in IGPs.

21.5.1 Saline and Water Logged Soil Reclamation

Trees like *A. nilotica, A. procera, C. equisetifolia, Dalbergia sisoo, Eucalyptus tereticornis, Melia composita, Pithecellobium dulce, Parkinsonia aculeata, Pongamia pinnata, Prosopis juliflora, Tamarix articulata, Terminalia arjuna, Tectona grandis, Salvadora spp.* and *Syzygium cuminii*, has been found suitable for saline soil agroforestry (Dagar et al. 2016a; Dagar et al. 2008). Fruit trees like *A. marmelos, Carrisa carandas, Emblica officinalis, Punica granatum, Syzygium cumini*, and *Tamarindus indica* has also been proved beneficial for reclamation and utilization of saline soils (Dagar et al. 2008; Dagar et al. 2016a, 2016b).

A. marmelos, *Emblica officinalis* and *Carrisa carandas* trees integration on saline soil with cluster bean (during *kharif*) and barley (in *rabi*) under moderate (ECiw 4–5.8 dS m^{-1}) to high degree of salinity (ECiw 8.2–10.5 dS m^{-1}) and water logging has been found suitable based on good yield of these (Dagar et al. 2008; Dagar et al. 2016a, 2016b).

Silvipasture system by integrating *Prosopis juliflora* and *Leptochloa fusca*, *B. mutica* and *Sporobolus* spp. of grass can be established for reclaiming saline soils as it has been reported to enhance soil nutrients and organic carbon status up to 30 cm depth within just in six-years (Dagar et al. 2008; Dagar et al. 2016a, 2016b).

Eucalyptus in block plantation has been utilized in Indo-gangetic plains for reclamation of water-logged soils and it transpired about 68.0, 71.5, and 73.8 L water day^{-1} $tree^{-1}$ under spacing of 1 m $\times$ 1 m, 1 m $\times$ 2 m, and 1 m $\times$ 3 m respectively. This has led to the lowering of water table up to 43.0 cm, 38.5 cm and 31.5 cm under 1 m $\times$ 1 m, in 1 m $\times$ 2 m, and i1 m $\times$ 3 m spacing, respectively after four year of planting (Dagar et al. 2016a, 2016b).

21.5.2 Sodic Soil Reclamation

Many agroforestry systems like fruit tree based and silvipastures have been tried under Indo-gangetic plains for reclamation of sodic soils. After 20 years of planting of *Prosospis juliflora*, *A. nilotica*, *Eucalyptus tereticornis*, *A. lebbeck* and *Terminalia arjuna,* it has been found that sodic soil reverted back to normal condition that agricultural crops can be grown successfully on it (Singh and Gill 1992). Fruit trees like, *Ziziphus mauritiana*, *Syzygium cuminii*, *Psidium guajava*, *Emblica officinalis* and *C. carandas* have also been found to grow perfectly on sodic soils and they yield good quantity fruit yield (12–25 t ha^{-1}) fruits annually (Dagar et al. 2001). Planting of trees like *Eucalyptus tereticornis*, *A. nilotica*, *Prosopis juliflora* and *C. equisetifolia* have been found to grow successfully on sodic soils in Uttar Pradesh yielding 231, 217, 208, and 197 kg bole after 14 years respectively and reduce soil pH, exchangeable sodium percentage and increase soil organic carbon (Singh et al. 2008).

(Singh 1995) has reported that under irrigated & moderate alkali soil conditions (pH 9.2) rice–wheat; rice–Egyptian clover; pigeon pea/sorghum–mustard rotations can be successfully integrated under *A. nilotica*, *Eucalyptus tereticornis*, *Populus deltoides* can be integrated successfully for proper utilization of the alkali soils.

Silvipastures has also been found successful in their potential to reclaim and utilize the sodic soil and sustain fodder supply in Indo-gangetic plains. Grasses like *Leptochloa fusca*, *C. gayana*, *Panicum maximum*, *Setaria anceps* can be integrated successfully with fodder trees like *Prosopis juliflora, A. nilotica*, *Dalbergia sissoo*, *C. equisetifolia* on sodic soils for high fodder biomass production and to decrease pH and enhance nutrient status of sodic soils (Singh and Dagar 2005). *Dalbergia sissoo* (Spacing: 6 m × 4 m) + paddy + wheat and *Dalbergia sissoo* (Spacing: 6 m x 4 m) + *Pennisetum purpureum* + *Brachiara mutica* + *Panicum maximum* based silvipasture has been found most suitable for utilizing the sodic soil effectively in IGPs region of Uttar Pradesh (AICRP-AF 2016).

21.5.3 Ravine Area Reclamation

Agri-horticulture system with integration of agricultural crops with fruit trees viz. *C. limon*, *Mangifera indica*, *Ziziphus mauritiana,* and aonla *Emblica officinalis* can be established successfully in gully beds (Verma et al. 1986). Grass species are known to form thick mat on soil thereby reduce soil erosion, therefore are important for reclamation of ravines. Grasses like *B. mutica, C. ciliaris, C. setigerus, Dicanthium annulatum, Panicum antidotale, Panicum maximum, Pannisetum purpureum* can be planted in ravine areas for sustaining fodder supply and reducing soil erosion. These grasses have been found to produce 18–20 t ha^{-1} $yr.^{-1}$ fodder on their successful establishment and reduced runoff to tune of 6–10 t ha^{-1} $yr.^{-1}$ (Chaturvedi et al. 2014). *A. nilotica* + *Acacia tortalis* + *C. ciliaris* and planting of indigenous Bamboo species with *C. ciliaris* forming silvipasture system can be established to enhance ravine land productivity (Prajapati et al. 1993); (Chaturvedi et al. 2014). These systems can be followed for reclamation of ravines in the Indo-gangetic plains.

21.6 Challenges in up Scaling of Agroforestry in Indo-Gangetic Plains

Traditionally, agroforestry has been practised in Indo-gangetic plains since antiquity to meet out the local/household demand for food, fodder, fruit, fibre, fuel wood, timber, herbal-medicines and non-timber forest products. With the passage of time and birth of industrial plywood company, WIMCO Limited, Poplar and Eucalyptus-based agroforestry got a huge boost and farmers came forward to take up this agro-forestry system on large scale. Almost 50% farms of the region were devoted for Poplar and Eucalyptus-based agroforestry as WIMCO Limited assured market for sale of poplar-Eucalyptus tree wood (Pathak and Pateria 1999; Chandra 2001). Agroforestry is an economical viable option for ensuring food, fodder, fruit, fibre, fuel wood, timber, nutrition, employment and environmental security in India. Except for Poplar and Eucalyptus-based agroforestry, other modern agroforestry practices still remain unutilized in the Indo-gangetic plains especially those focusing on reclamation of salt affected soils, ravines and degraded lands. Moreover, not all the farmers (especially small & marginal) in IGPs are ready to adopt agroforestry technologies due to socio-cultural, economic, infrastructural and policy issues.

First and foremost factor that deters farmers to take up agroforestry is lack of awareness regarding tangible and non-benefits of it and they presume planting of trees on farm area will decrease crop productivity. Large farmers have successfully established agroforestry models on their farm which may not be beneficial for small and marginal farmers. Thus, focus needs to be given on, on-farm research trial involving these farmers to develop agroforestry model for their economic upliftment. Lack of institutional infrastructure; credit, insurance and market support is another factor for lack of large scale adoption of agroforestry in IGPs. There is restriction on felling of farm grown tree species except for a few of them and there no homogeneity regarding, laws and regulations related to felling, transporting and sale of farm-grown timber species and their non timber forest products. Moreover, like agricul-ture crop there is no provision for minimum support price for timber and non-timber forest produced from there agroforestry systems. These, these laws and regulations varies from state to state and needs to made farmer more friendly by allowing them to fell and sale farm grown timber species. These rules must be farmer supportive for successful and large scale adoption of agroforestry in IGPs.

Lack of availability of superior and quality planting stock of trees and certifica-tion scheme for tree based products produced from agroforestry systems is also a constraint in large scale adoption of agroforestry. There is not check on farmer exploitative marketing channels by government agencies. Further no scheme is there to train the farmers, build their skills and capacity related to establishing; managing the agroforestry models and to encourage them to taking up agroforestry. Due to theses specific constraints farmers are not taking up agroforestry practices on large scale despite of multiple economic and ecological benefits of agroforestry.

21.7 Role of Research Institutions in Streamlining Agroforestry Research in IGPR

India has been at the forefront ever since organized research on agroforestry was started worldwide. I.C.A.R. launched an All India Coordinated Research Project on Agroforestry (AICRPAF) with 20 centres in 1983. At present there are 37 centres representing all the agroclimates in the country. This was followed by establishment of a National Research Centre on Agroforestry on eighth May, 1988 at Jhansi, U.P. which was later on upgraded as Central Agroforestry Research Institute in 2014. Under the National Agriculture Research System (NARS) about 30 SAUs have established Forestry/agroforestry departments besides two exclusive University on Horticulture & Forestry at Solan in Himachal Pradesh and at Barsar in Uttrakhand. Besides, NARS, a network of 11 ICFRE institutes/centres and six State Forest Research Institutes are also conducting limited agroforestry research.

Initially, three core projects were started through AICRPAF. These were – the Diagnostic and Design Survey of the agroforestry practices, Collection and Evaluation of MPTS; and Management of Agroforestry Systems. The Diagnostic and Design survey by the centres generated valuable information and identified important agroforestry practices from different parts of the country. A compilation on these D&D survey has already been published entitled, Agroforestry Systems in India: A Diagnosis & Design Approach. The collection and evaluation of MPTS resulted in establishment of arboretum in each centre. A collection of 184 species was made by the centres. This followed by identification of priority tree species of agroforestry research for various agroclimates. Each centre was allocated two tree species for germplasm collection and provenance trials. A significant contribution of the project was on Tree Selection and Improvements for tree species such as Poplar, Eucalyptus, Dalbergia, Neem, Acacia, Leucaena, Ailanthus, Pongamia, Casuarina and Mangium hybrids. Clonal seed orchards for Dalbergia, Acacia and some more species have been established. Under NATP a “agroforestry BASE” database has been developed which is online. It is updated periodically. Agroforestry research was further strengthened by grant of AP Cess Ad-hoc Research Projects by ICAR. The Technology Extension Project on Agroforestry was conducted by the centres with funds from Department of Wasteland Development MOEF. It strengthened the transfer of agroforestry technologies in the farmer’s field. In addition agroforestry practices have been intertwined in the various programs/schemes like watershed development and so on.

The national research system has generated significant scientific outputs in this area and is poised to accelerate the efforts. Now potentials of large impacts from agroforestry are well recognized by the government and private sector. A large private sector industry has already developed around several tree products and there are good examples where agroforestry has made a significant impact on the economy, livelihoods and landscapes. Poplar and Eucalyptus based agroforestry in Indo-Gangetic region; Eucalyptus and Leucaena based agroforestry in Andhra Pradesh and other southern states; Ailanthus based in Gujrat are successful examples to name a few. However, there are certain areas where now concerted efforts are needed. It is realized that further to guide agroforestry efforts in India is the criteria of "high value low volume system concept". The other important criteria are the post-harvest, value addition, packaging and marketing aspects, which are to be made integral part of the system as a whole. One important consideration is the recognition of the fact that agroforestry system also provide environmental services in addition to the economic gains and other contributions. Incorporation of trees in the farming system may be one of the ways to mitigate some of the climate change effects. It is worth mentioning here that agroforestry systems are probably the only means for getting the desired tree cover in the country, especially in states that have low tree cover.

Over the span of about four decades of systematic research in agroforestry has already shown that it can contribute significantly to meet the, deficits in fuel, fodder, timber, accelerate economic growth; help in poverty alleviation; women empowerment and livelihood support in several ways. Agroforestry has played significant role in rehabilitation of degraded lands, bioremediation of problem soils and reclamation of waterlogged soils through bio-drainage. It is estimated that at present about half of the country's timber requirement is produced through agroforestry.

The AICRP on AF centres located in the region have successfully developed package of practices for Poplar, Eucalyptus based agroforestry systems. The recent studies conducted by (Rizvi et al. 2020) reported about 0.276 million ha in Punjab and 0.205 million ha in Haryana under poplar based agroforestry.

21.8 Way Forward

The Agroforestry Policy of India has lead the way forward to upscaling agroforestry among different stakeholders. It is true that agroforestry could play a major role, not only for food and livelihood security, but also in combating the environmental challenges. Agroforestry and trees outside forest will be a key issue in providing solutions to climate change and improving the per unit land productivity. The major focus of research in the coming years will be on developing agroforestry technologies for higher productivity and natural resource management. Therefore, there is a need for development of agroforestry models linked with market for enhancing productivity and profitability and agroforestry models for mitigation of climate change effects. This will ensure stabilization of production and productivity, meeting basic needs, minimize ecological degradations and sustainable management of land, water and biodiversity. A major role for agroforestry in near future will be in the domain of environmental services, such as climate change mitigation (carbon sequestration), phytoremediation etc. However, still many issues need to be resolved for which more coordinated, focused, determined efforts are required from all the research institutions. Future areas of agroforestry need to include the following issues:

- Development of agroforestry models for small holders.
- Institutionalize infrastructure, credit, insurance and market support for large scale adoption of agroforestry in IGPs.
- Development of agroforestry models for multiple output production.
- Diversification through agroforestry and other alternate land use systems.
- Development of management techniques to reduce above and below ground competition.
- Development of quality planting material for higher productivity.
- Capacity building of the stakeholders.
- Support price for farm-grown timber tree products.

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