Deepak G. Panpatte · Yogeshvari K. Jhala
Editors

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Preface

Soil is the vital element of earth, and its fertility is very important for supporting all the living forms. Soil fertility is the capacity to receive, store, and transmit energy to support plant growth. These processes require healthy soils – living, self-organizing systems with physical, chemical, and biological components all functioning and in balance. During the era of green revolution, there was an increase in agricultural production. Meanwhile, to increase production, there was an increase in the use of chemical-based agro-inputs which disturbed natural balance of soil. The long recommended use of fertilizers, pesticides, and other synthetic chemicals to address problems in agricultural production has been leading to poor soil health and resistance in insects, diseases, and weeds. Presently, cultivators are using chemical agro-inputs and totally ignoring delicate balance of humus, microbes, trace minerals, and nutrients in the soil which results in soil degradation resulting in reduction in the capacity of the soil to feed plants.

Good management of soils ensures balance of physical, chemical, and biological properties of soil, and that's how appropriate mineral elements enter the food chain. For maintaining crop productivity, environmental sustainability, and healthy living beings, the management of soil is of prime importance. In many communities of the world, soil is being worshiped like a mother as it is nurturing life. To achieve the goal of sustainability of agro-ecosystem and food security, soil fertility management in sustainable manner reduction of soil degradation is the challenge. Soil management in the soil is supported by better organic carbon content, suitable mineral balance, and a varied and copious soil life. Biological components of soil help in building and maintenance of soil structure and functioning.

The book entitled *Soil Fertility Management for Sustainable Development* addresses the important aspects of soil fertility management, with the help of reputed national and international scientists working in the field of soil fertility management. Each chapter will emphasize on the mechanism of action and recent advances in the techniques for improvement of soil fertility. The outlooks of the authors are methodical and firm based on their own experiences during their carrier in the field of soil fertility management. I hope this book will be extremely useful to the researchers in the field of agriculture especially those who are working on the development of newer strategies for soil fertility management as a source of valuable information.

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Introduction

Soil fertility is the stepping stone for determining productivity of all farming systems. Generally, our interpretation for the term soil fertility is the "capacity of soil to provide nutrients to the crop." If we look at a wider scenario, then soil fertility does not only mean to provide nutrients, it also includes the capacity to support plant growth as well as physical, chemical, and biological properties of the soil. There exists a delicate balance between three main components of soil fertility, i.e., physical, chemical, and biological. Indiscriminate use of agrochemicals like synthetic fertilizers, insecticides, fungicides, and herbicides upsets the delicate equilibrium between the three components of soil fertility. The intension of soil fertility management is to improve soil buffering capacity to reduce soil degradation, improvement of soil nutrient status by biological nutrient cycling. If we look at the present scenario, people are just thinking about the nutrient status of the soil and nobody seems to be worried about the physical and biological properties of the soil. Fertile soil in true sense can be defined as a soil comprising of well-balanced nutrients, high organic matter with good physical strength, and abundant soil life. The biology of soil, i.e., microorganisms and macroorganisms is the prime indicator of soil health. So, looking to the present scenario management of soil fertility in sustainable manner is demand of the time, and we seriously have to work hard for this; otherwise, in the near future, our soils will become barren with no capacity to support the life.

The present book enriches our knowledge about the various aspects of soil fertility management including microorganism-based strategies, the use of organic manures, biochar, seaweed, and mulching as well as site-specific nutrient management system for enhancement of soil fertility. The readers will be enriched with a detailed account of all the aspects that are required for making a soil "fertile." The views of the authors are thorough and authoritative based on their long research experience in the subject area. We hope that this book will be very useful for all those who are actively involved in the research on soil fertility management for apprehending its benefit in sustainable agricultural productivity.

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About the Editors

Dr. Deepak G. Panpatte has been working as a research scholar for the past 7 years. His research interests include agriculturally beneficial microorganisms such as biofertilizers, biopesticides and biodegraders. Done pioneering work for development of fortified biocontrol bacterial consortium with phyto-extracts for management of phytopathogenic nematodes and fungi. He has received 5 awards for presentation of research outcomes in International conferences and Rastiya Gaurav Award for outstanding contribution in agriculture. His publication profile includes 14 research papers, 2 books & 9 book chapter with Springer publishing house, 1 practical manual, 26 popular articles and 2 editorial pages.

Dr. Yogeshvari K. Jhala is an Assistant Professor with 10 years of teaching and research experience. Her field of interest is agriculturally beneficial microorganism such as biofertilizers, biopesticides and biodegraders. She was the first researcher worldwide to report 5 unique strains of methanotrophic bacteria. She has received the All India Best Research Award and Young Faculty Award for her outstanding research on methanotrophic bacteria. Her publications include 17 research papers, 2 Books, 6 book chapters, 2 teaching manuals, 18 popular-science articles and 2 editorial pages.

1 Phosphorus Capture, Immobilization and Channeling Through Algae for a Sustainable Agriculture

D. M. Mahapatra, R. Mahapatra, L. Singh, H. J. Kadhum, G. S. Murthy, H. N. Chanakya, N. V. Joshi, and T. V. Ramachandra

Abstract

Excessive use of phosphorus (P) based fertilizers for improved agricultural productivity has resulted in nutrient enrichment and consequent deterioration of surface and ground waters. Naturally, available soil microbes in an agricultural set-up are capable of mineralization of organic P and/or solubilisation of inorganic P thus making it bioavailable to the crop systems. As an alternative to conventional P based fertilizers, wastewater rich in nutrients can be cheap and economic P sources ensuring phosphorous recycle and reuse. However, the treatment of these waters to check pathogens, heavy metals and other toxicants; conveyance and storage are practical constraints that limits the usage of wastewaters directly to croplands. Wastewater grown algae as proficient biofertilizer can be potentially used to immobilize P and channelize P to croplands. Such algal biomass abundantly growing in natural waters as well as in treatment ponds can be

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rich sources of nutrients due to their higher P uptake abilities, growth rate and productivity. Although there are huge opportunities for using algae as a bio-filter to recover P from wastewater streams. However, their use for tapping valuable P with present day technologies are still evolving and are in infancy. Efforts on understanding the mechanism of P uptake, immobilization in algal cells and subsequent P transport to agricultural soil systems are important. This can provide global solutions in stocking wastewater P and its sustainable reuse as algal-based P rich biofertilizer.

Keywords
Phosphorus · Immobilization · Algae · Agriculture · Biofertilizer · Sustainability

1.1 Introduction

P is crucial in crop development and growth, comprising of ~0.2% of crop plants dry weight. After nitrogen, it is the second most important nutrient limiting the crop growth (Kvakic et al. 2018). Although 0.5 kg P/ton of agricultural soil is naturally found, but only 0.5 g of soil bound P is actually available for plant uptake. Conventional agricultural practices have minimized the inadequacy of the P in soils through external application of P rich fertilizer. Such practices over decades has resulted in environmental externalities as nutrient enrichments in surface and ground waters (Bauke et al. 2018). This necessitates identification of potential alternatives to chemically fixed synthetic fertilizer and explore possible microbial immobilization and channeling strategies for sustainable agriculture.

Microbiota is soils perform nutrient mineralization and thus aid in nutrient assimilation in crops. They are mainly involved in breaking down complex insoluble organic/inorganic forms into simpler ions through solubilization/mineralization (Menezes-Blackburn et al. 2017). An array of pedosphere microbiota associated with the rhizosphere are generally known for P mineralization, solubilisation and mobilization in plants (Turner et al. 2015) and are referred as P solubilizing microbes

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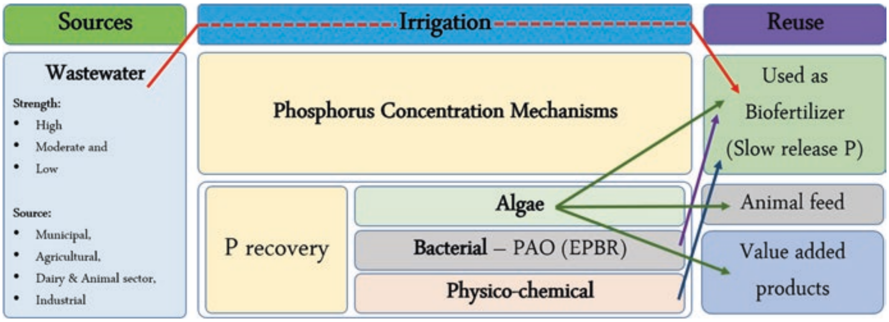

Fig. 1.1 Various mechanisms of P recovery from wastewater with emphasis on algal route

(PSM). Some stress tolerant microbes as halophiles also aid in solubilizing P from alkaline soils (Sharma et al. 2013). Propagating such suitable and select microbes are smart ways for soil nutrient enrichment that directly evades the risks of application of costly chemical fertilizers and restricts environmental damages (Nath et al. 2017).

Capturing nutrients from wastewaters through its direct application or through temporary immobilization by beneficial algal communities are attractive solutions for closing the phosphorus cycle ensuring reusability and ecological gains (Sharma et al. 2013). Wastewaters could be potential nutrient hubs for agricultural food security. However, there can be several constraints in its utility (a) quality concerns (pathogens/toxins) (b) time for storage and preserving the nature of the dissolved nutrients as crops have seasonality (c) transportation to various agricultural locations (for applications of 1 ton of P around 150 kilotons of wastewater is required). Wastewater as potential P sources albeit effective are however challenging in terms of treatment, storage and transportation costs (Shilton et al. 2012). If, the irrigational requirements are met, a suitable way for nutrients application to agricultural crops is through temporary immobilization of dissolved forms in the form of algal biomass. This nutrient rich algal biomass can be directly applied to these croplands and potentially acts like slow release fertilizer as elucidated in Fig. 1.1.

P recovery from wastewaters have been carried out through adsorption based processes, precipitation and bacterial process in enhanced biological phosphorus removal (EBPR) and have been explained in earlier studies (Pratt et al. 2012; Yuan et al. 2012). Algae owing to high ubiquity, tolerance, faster growth rates and adaptations have been recently witnessed as a most attractive biological agent for capturing nutrients as phosphates and provides a huge scope for sustainable technology development for harnessing nutrients.

1.2 Microbial Phosphorus Immobilization

Microbiota in soil systems as cyanobacteria, bacteria and fungi with other soil organisms help in efficient nutrient cycling of P through mineralization and P immobilization (Barea and Richardson 2015). P mobilization from organic and

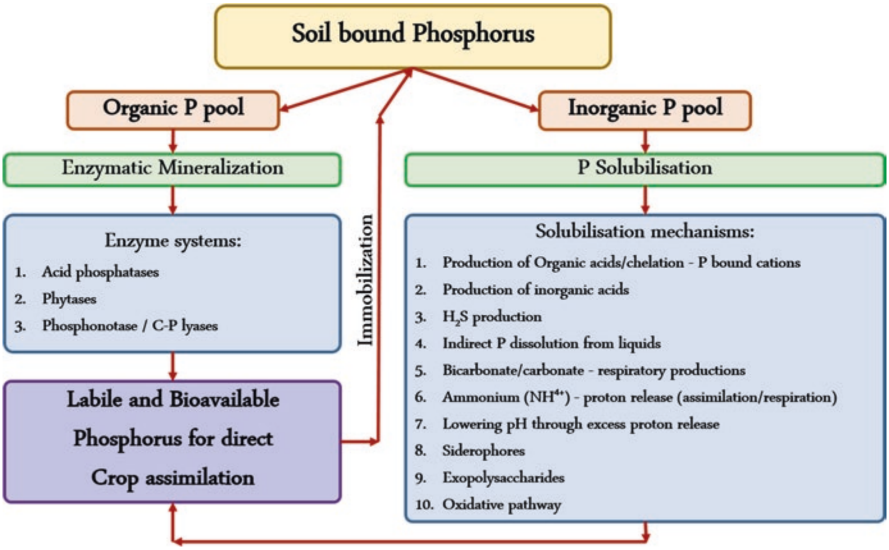

Fig. 1.2 Schematics of P transfer routes in agricultural soil systems through mineralization and solubilisation

inorganic P pools are carried out through enzymatic mineralization and insoluble P solubilisation respectively through various mechanisms i.e. carboxylates, phosphatases; exuding protons to release inorganic labile phosphates (Sharma et al. 2013) as provided in Fig. 1.2. PSM are groups of microbes comprising of bacterial members as *Agrobacterium* sp., *Bacillus* sp., *Erwinia* sp., *Flavobacterium* sp., *Micrococcus* sp., *Pseudomonas* sp., *Rhizobium* sp. and fungal members as *Aspergillus* sp., *Penicillium* sp. and *Trichoderma* sp. (Sharma et al. 2013; Srinivasan et al. 2012). In some cases the available P in soil systems are uptaken by soil microbes and becomes a part on microbial biomass phosphorus. Such conditions facilitates rapid organic C uptake of root exudates for meeting the energy requirements (Wu et al. 2007). Phosphorus that is trapped in the microbial biomass often gets released back into the soil available P pool during microbial genesis and is dependent on the environmental conditions as soil nutrient pool, seasonality and soil moisture (Butterly et al. 2009). Estimates have shown that influx of P from microbial biomass P pools can range from 18 to 36 kg P/ha/season especially during summer and fall (Liebisch et al. 2014).

The P availability is dependent on the relative concentration of P pools in soil systems and the microbial biomass P. In highly bioavailable soil P conditions, usually the microbial biomass P have been found to be low (Marschner 2008). These dynamics are governed largely by a number of factors as the soil carbon to phosphorus ratio (Spohn and Widdig 2017). At squat C:P levels, microbial P pools are low (Kouno et al. 2002); attributed to C limitations and moreover, the microbial P pools increase with increase in C:P ratio (Cleveland and Liptzin 2007). Over the years with applications of enriched P based fertilizers, there has been a decline in the C:P ratio, that demands an increase in the C:P ratio so that substantial amount of P can be immobilized back into the microbial biomass P pools (Xu et al. 2015). Investigations on soil P dynamics have witnessed a lower microbial biomass P pool in intensive agricultural zones (Oberholzer et al. 2014) compared to forest and grassland ecosystems (lower C:P ratio) attributed to removal of C rich above ground biomass (Bender et al. 2016). Thus, provisions for additional C supplementation into the soil would help in better P immobilization in such systems. Addition of C rich plant residue or organic amendments can increase the microbially fixed biomass P phenomenally.

One of the major measures for enhancing the C content of the soil is by the application of wastewater grown algal biomass that not only provides nutrients as P to the soil systems but also improves the soil C that is required for higher microbial diversity and P pools (Mahapatra et al. 2017). Such algal biomass can be grown from a variety of wastewaters as dairy, municipal or agricultural i.e. nursery wastewaters. Our recent studies on alga grown on leachate (Naveen et al. 2016; Rajendran et al. 2018); high strength flushed manure wastewater and municipal wastewaters (unpublished data) have shown higher algal productivity with enhanced nutrients capture. This algal biomass can be utilized both as biofertilizer as well as for improving the C:P ratio in the soil for ensuring higher microbial biomass P pools, that helps in the improving the nutrients status of the soils and its long term sustainability in agricultural food production. Moreover, the algal biomass can be also mixed with other agricultural residues for a resilient and vibrant phosphorus economy and biorefinery. This approach helps in developing circular bio-economy and dramatically reduces the nutrient loads on the environment. However, it will be interesting to note the mechanisms of C mobilization after its land applications, potential mineralization and associated emissions from the soil and its implications on the availability of other essential minerals to the plants. Moreover, any possible changes in the soil microbiota can also be beneficial for the complex agricultural systems and over a period might enhance the diversity of microbes for a green and sustainable agricultural future.

1.2.1 Algae Mediated P Immobilization and Channelization

Algae are cosmopolitan and have been now largely known for its effectiveness in treating wastewaters of various strengths and from diverse sources globally. Mostly, they have been used through conventional facultative ponds, high rate algal ponds (HRAP) and tubular photobioreactors (Abis and Mara 2003; Craggs et al. 2014). However, in such systems phosphorus removal and recovery have not been specifically undertaken (Garcia et al. 2000). The conventional facultative ponds/lagoons are highly effective in reducing the nutrient loads through efficient nutrient capture and have resulted in substantial pathogen reduction. These facultative ponds systems have not been capitalized for targeting nutrient rich biomass cultivation and subsequent harvest. On, the other hand HRAP's are being used for mass scale production of algal biomass and thus can be optimized for higher productivities and

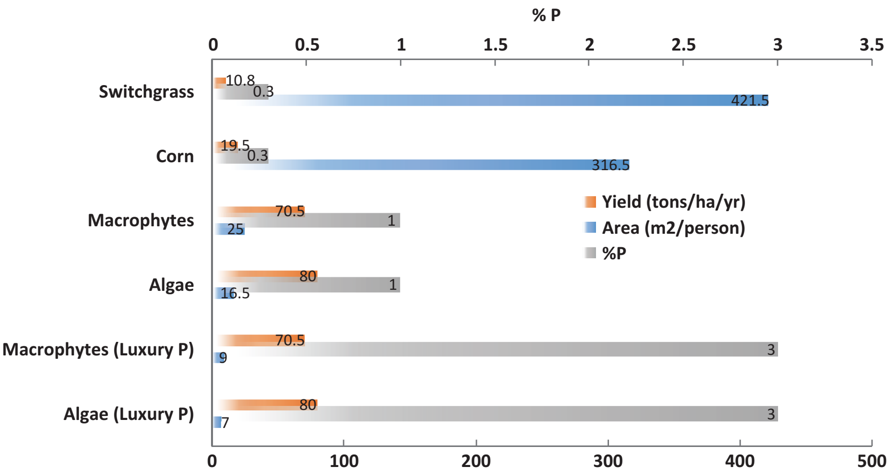

Fig. 1.3 Bar chart indicating comparative area requirement, yields with P quantity in agricultural substrates (switch grass and corn); Macrophytes and Algae with nominal P content (~1%) and Macrophytes and Algae with high P content (3%, luxury P uptake)

bioproducts yields. This is performed through various manipulations in (a) micro-environmental and physico-chemical factors (inorganic C additions, low pH conditions) (b) reactor design and configuration (provisions for effective mixing, enhancing mass transfer, shallow reactor depths and shorter residence times). More often it has been observed that the P content of wastewater algae are comparatively high due to the phenomenon of luxury P uptake (Shilton et al. 2012). The P content in wastewater algae can be as high as 3.3% (Powell et al. 2008) compared to ~0.5 to 1%, typically observed in algal biomass. These observations have been also confirmed through our earlier studies with mixotrophic algal, unialgal and co-cultures (Mahapatra et al. 2013a, 2014; Mahapatra 2015) cultivated with municipal wastewaters and have been witnessed in other studies as well (Powell et al. 2008).

It has been shown that the luxury P uptake in case of these algal communities directly depends upon, the temperature, light intensity and inorganic P concentrations in the growth media (Fanta et al. 2010; Cade-Menun and Paytan 2010; Sforza et al. 2018). Possibilities of concentrating phosphorus in P rich (~3% of the biomass by weight) algal biomass are in progress, and can potentially reduce the area requirements in P recovery via HRAP to 5.5 m^2/capita (Fig. 1.3). This dramatically reduces the costs for harvesting, conveying and spreading it on agricultural land as biofertilizer by factor of 0.6 as compared to usual algae/organic substrates with P content <1%. On one hand, the facultative ponds have their own advantages in treatment and harbor beneficial motile flagellate algal communities i.e. *Euglena* spp. and *Chlamydomonas* (Mahapatra 2015) and non-motile algae as *Chlorella* and *Chlorococcum* (Mahapatra et al. 2013b, 2018; Mahapatra and Ramachandra 2013). On the other hand, ongoing innovations in multimodal algal bioprocess design have been targeting various strategies for efficient harvesting i.e. gravity based, flocculants, and other polymer-mediated methods (unpublished data). There have been studies that have proved efficient harvest with the help algal cells immobilized as beads made up of alginate, carrageenan and chitosan, (De-Bashan and Bashan 2004) for efficient P recovery. The immobilization media also facilities P retention through adsorption and precipitation (De-Bashan et al. 2004). Studies have revealed >90% P removal with chitosan immobilized *Scenedesmus* (Fierro et al. 2008). Recently algal turf scrubbers with the immobilized attached algal community's grown as biofilm communities over various kinds of surface are being used for treatment of dairy (Mulbry et al. 2008; Prabakar et al. 2018), agricultural (Kangas and Mulbry 2014) and swine facility wastewater (Kebede-Westhead et al. 2006).

Algal derived phosphorus can be highly valued resource under today's regime of nutrient scarcity. Globally, voluminous wastewater discharge enriches large surface water resources. These water resources can be filtered from nutrients through algal technologies and can be directly applied as slow release fertilizers into the agricultural areas that ensures a biorefinery approach thereby completely closing the nutrient cycles. The typical architecture of a facultative ponds and lagoons especially in tropical waters have multi-tier algal communities that help in efficient nutrient remediation, and wastewater purification (Mahapatra et al. 2011a, b, c; Chanakya et al. 2012, 2013; Mahapatra 2015; Mahapatra et al. 2017). The experiments on algal cultivation with high strength wastewater i.e. municipal wastewaters have demonstrated higher nutrient recovery and biomass productivity with high P concentrations in unialgal and polycultures especially with the mixotrophic community (Mahapatra et al. 2013a, b, c, d, e, f, 2014, 2017). Wastewater treatment systems involving facultative ponds have shown a higher techno-economic feasibility for algal single cell proteins i.e. euglenoides (Mahapatra et al. 2016) and as biofertilizer as *Spirulina* sp. (Mahapatra et al. 2018) with a lower environmental impact (Ramachandra et al. 2009; 2012; Ramachandra and Mahapatra 2012; 2015; Ramachandra et al. 2015). A modular algal bioprocess designed at the Indian Institute of Science (IISc), Bangalore, have been successfully working for nutrient capture and recovery at the Jakkur Lake in Bangalore City and similar plans for implementation of the technology for lake rejuvenation in Varthur, Bellandur and other lakes in Bangalore are in progress(Ramachandra et al. 2013; 2014; Mahapatra 2015; Ramachandra et al. 2016; 2017a, b, c).

1.3 Future Scope and Conclusion

Widespread application of phosphorus rich fertilizers aiming higher agricultural productivities have resulted in higher P loses and subsequent enrichment in surface and ground waters. This necessitates for an efficient alternative to P rich inorganic fertilizers and at the same time, facilitate provisions for the greater immobilization of P in soil systems to abate such loses and evade the resulting environmental externalities. Algal cultivations through pond systems are becoming prevalent for both nutrient remediation and biomass production. Use of wastewater-grown algae and algal biomass addition for improvement of soil nutrient conditions coupled with facilitating higher soil carbon amendments is an attractive option and ensures greater fertilization with minimal losses linked with leaching and runoff. The harvested algal biomass takes less than one-tenth of the area to capture P compared to agricultural crops and grass species. With the help of algal species having high cellular P content, the area required for capturing P can be even further reduced. More research efforts on ground with full-flagged algal bio-refineries can aid in better understanding of phosphorus dynamics and identify crucial pathways for capturing P. Focus on (a) maximize algal P content (b) increase algal productivity (c) newer and cheaper methods of harvesting algae and (d) understanding algal phosphorus mobilization, mineralization and consequent assimilations by agricultural crops will pave path for sustainable agricultural economy.

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References

Abis KL, Mara DD (2003) Research on waste stabilization ponds in the United Kingdom: initial results for pilot-scale facultative ponds. Water Sci Technol 48:1–7

Barea JM, Richardson AE (2015) Chapter 24: Phosphate mobilisation by soil microorganisms. In: Lugtenberg B (ed) Principles of plant-microbe interactions. Springer, Cham, pp 225–234

Bauke SL, von Sperber C, Tamburini F, Gocke MI, Honermeier B, Schweitzer K et al (2018) Subsoil phosphorus is affected by fertilization regime in long-term agricultural experimental trials. Eur J Soil Sci 69:103–112

Bender SF, Wagg C, van der Heijden MGA (2016) An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol Evol 31:440–452

Butterly CR, Bünemann EK, McNeill AM, Baldock JA, Marschner P (2009) Carbon pulses but not phosphorus pulses are related to decreases in microbial biomass during repeated drying and rewetting of soils. Soil Biol Biochem 41:1406–1416

Cade-Menun BJ, Paytan A (2010) Nutrient temperature and light stress alter phosphorus and carbon forms in culture-grown algae. Mar Chem 121:27–36

Chanakya HN, Mahapatra DM, Sarada R, Chauhan VS, Abitha R (2012) Sustainability of largescale algal biofuel production in India. J Indian Inst Sci 92(1):63–98

Chanakya HN, Mahapatra DM, Sarada R, Abitha R (2013) Algal biofuel production and mitigation potential in India. Mitig Adapt Strateg Glob Chang 18:113–136

Cleveland CC, Liptzin D (2007) C: N: P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass? Biogeochemistry 85:235–252

Craggs R, Park J, Heubeck S, Sutherland D (2014) High rate algal pond systems for low energy wastewater treatment, nutrient recovery and energy production. N Z J Bot 52:60–73

De-Bashan LE, Bashan Y (2004) Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003). Water Res 38:4222–4246

De-Bashan LE, Hernandez JP, Morey T, Bashan Y (2004) Microalgae growth-promoting bacteria as “helpers” for microalgae: a novel approach for removing ammonium and phosphorus from municipal wastewater. Water Res 38:466–474

Fanta SE, Hill WR, Smith TB, Roberts BJ (2010) Applying the light: nutrient hypothesis to stream periphyton. Freshw Biol 55:931–940

Fierro S, Sanchez-Saavedra MP, Copalcua C (2008) Nitrate and phosphate removal by chitosan immobilized *Scenedesmus*. Bioresour Technol 99:1274–1279

Garcia J, Mujeriego R, Bourrouet A, Penuelas G, Freixes A (2000) Wastewater treatment by pond systems: experiences in Catalonia. Spain Water Sci Technol 42:35–42

Kangas P, Mulbry W (2014) Nutrient removal from agricultural drainage water using algal turf scrubbers and solar power. Bioresour Technol 152:484–489

Kebede-Westhead E, Pizarro C, Mulbry WW (2006) Treatment of swine manure effluent using freshwater algae: production, nutrient recovery and elemental composition of algal biomass at four effluent loading rates. J Appl Phycol 18:4–46

Kouno K, Wu J, Brookes PC (2002) Turnover of biomass C and P in soil following incorporation of glucose or ryegrass. Soil Biol Biochem 34:617–622

Kvakic M, Pellerin S, Ciais P, Achat DL, Augusto L, Denoroy P, Gerber JS, Goll D, Mollier A, Mueller ND, Wang X, Ringeval B (2018) Quantifying the limitation to world cereal production due to soil phosphorus status. Global Biogeochem Cycles 32:143–157. https://doi.org/10.1002/2017GB005754

Liebisch F, Keller F, Huguenin-Elie O, Frossard E, Oberson A, Bünemann EK (2014) Seasonal dynamics and turnover of microbial phosphorus in a permanent grassland. Biol Fert Soils 50:465–475

Mahapatra DM (2015) Algal bioprocess development for sustainable wastewater treatment and biofuel production. Ph.D. thesis, Indian Institute of Science, Bangalore, India

Mahapatra DM, Ramachandra TV (2013) Algal biofuel: bountiful lipid from *Chlorococcum* sp. proliferating in municipal wastewater. Curr Sci 105:47–55

Mahapatra DM, Chanakya HN, Ramachandra TV (2011a) Assessment of treatment capabilities of Varthur Lake. Bangalore Int J Environ Technol Manag 14(1–4):84–102

Mahapatra DM, Chanakya HN, Ramachandra TV (2011b) Role of macrophytes in urban sewage fed lakes. I. Inte Omics Appl Biotech 2(7):1–9

Mahapatra DM, Chanakya HN, Ramachandra TV (2011c) C: N ratio of sediments in a sewage fed urban Lake. Int J Geol 5(3):86–92

Mahapatra DM, Chanakya HN, Ramachandra TV (2013a) *Euglena* sp. as a suitable source of lipids for potential use as biofuel and sustainable wastewater treatment. J Appl Phycol 25:855–865

Mahapatra DM, Chanakya HN, Ramachandra TV (2013b) Treatment efficacy of algae based sewage treatment plants. Environ Monit Assess 185:7145–7164

Mahapatra DM, Chanakya HN, Ramachandra TV (2013c) Nano-scale characterization of wastewater euglenoides with Scanning Electron Microscope (SEM). In: Proceedings of 6th Bangalore India NANO. Hotel Lalit Ashok, Bangalore, India, 5–6th December 2013, p. 73

Mahapatra DM, Chanakya HN, Ramachandra TV (2013d) Raman micro-spectroscopy for characterization of lipids in oleaginous algae in-vivo. In: Conference proceedings, FCS, national fluorescence workshop "fluorescence methods in single molecule spectroscopy" at IISc and JNCASR, Bangalore, India 24–28th, November 2013, p. 96

Mahapatra DM, Chanakya HN, Ramachandra TV (2013e) Sustainable wastewater treatment and biofuel generation for Bangalore City using continuous algal reactors. In: Proceedings of the Indo-UK perspective on water quality: threats, technologies and options, Royal Society of Chemistry. IISc Bangalore, Karnataka 13–14th, August 2013, p. 54

Mahapatra DM, Chanakya HN, Ramachandra TV (2013f) Bioenergy generation from components of a continuous algal bioreactor: analysis of lipids, spectroscopic and thermal properties. In: Proceedings of 10th IEEE INDICON conference on impact of engineering on global sustainability, IIT Bombay, India IEEE, Explore, pp. 183–184

Mahapatra DM, Chanakya HN, Ramachandra TV (2014) Bioremediation and lipid synthesis of myxotrophic algal consortia in municipal wastewater. Bioresour Technol 168:142–150

Mahapatra DM, Chanakya HN, Ramachandra TV (2016) Book chapter: algae derived single cell proteins: economic cost analysis and future prospects. In: Protein byproducts: transfor-

mation from environmental burden into value-added products, 1st edn. Elsevier, San Diego, pp 275–301
Mahapatra DM, Joshi NV, Ramachandra TV (2017) Insights to bioprocess and treatment competence of urban wetlands. J Environ Manag 206:1179–1191
Mahapatra DM, Varma VS, Muthusamy S, Rajendran K (2018) Wastewater algae to value-added products. In: Singhania R, Agarwal R, Kumar R, Sukumaran R (eds) Waste to wealth. Energy, environment, and sustainability. Springer, Singapore
Marschner P (2008) The role of rhizosphere microorganisms in relation to P uptake by plants. In: White PJ, Hammond JP (eds) The ecophysiology of plant-phosphorus interactions. Springer, Heidelberg, pp 165–176
Menezes-Blackburn D, Giles C, Darch T, George TS, Blackwell M, Stutter M, Shand C, Lumsdon D, Cooper P, Wendler R, Brown L, Almeida DS, Wearing C, Zhang H, Haygarth PM (2017) Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: a review. Plant Soil 427:5–16
Mulbry W, Kondrad S, Pizarro C, Kebede-Westhead E (2008) Treatment of dairy manure effluent using freshwater algae: algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresour Technol 99:8137–8142
Nath D, Maurya BR, Meena VS (2017) Documentation of five potassium and phosphorus-solubilizing bacteria for their K and P-solubilization ability from various minerals. Biocatal Agric Biotechnol 10:174–181
Naveen BP, Mahapatra DM, Sitharam TG, Sivapullaiah PV, Ramachandra TV (2016) Physicochemical and biological characterization of urban municipal landfill leachate. Environ Poll 220. (Part A:2–12
Oberholzer HR, Leifeld J, Mayer J (2014) Changes in soil carbon and crop yield over 60 years in the Zurich organic fertilization experiment, following land-use change from grassland to cropland. J Plant Nutr Soil Sci 177:696–704
Powell N, Shilton A, Pratt S, Chisti Y (2008) Factors influencing luxury uptake of phosphorus by microalgae in waste stabilization ponds. Environ Sci Technol 42:5958–5962
Prabakar D, Manimudi VT, Subha KS, Swetha S, Mahapatra DM, Rajendran K, Pugazhendhi A (2018) Advanced biohydrogen production using pretreated industrial waste: outlook and prospects. Renew Sust Energ Rev 96:306–324. https://doi.org/10.1016/j.rser.2018.08.006
Pratt C, Parsons SA, Soares A, Martin BD (2012) Biologically and chemically mediated adsorption and precipitation of phosphorus from wastewater. Curr Opin Biotechnol 23:890–896
Rajendran K, Sudharsan VV, Mahapatra DM, Kondusamy D (2018) Economics of solid waste management. In: Singhania R, Agarwal R, Kumar R, Sukumaran R (eds) Waste to wealth. Energy, environment, and sustainability. Springer, Singapore
Ramachandra TV, Mahapatra DM (2012) Scope of algal biofuel from wastewater. In: 8th National Conference on Indian energy sector "synergy with energy". Conference proceedings, AMA, Ahmadabad, Maharashtra, India, 11–12th October 2012
Ramachandra TV, Mahapatra DM (2015) The science of carbon footprint assessment. In: The carbon footprint handbook. CRC Press, Taylor & Francis Group, Boca Raton, pp 1–44
Ramachandra TV, Mahapatra DM, Karthick B, Gordon R (2009) Milking diatoms for sustainable energy: biochemical engineering vs. gasoline secreting diatom solar panels. Ind Eng Chem 48(19):8769–8788
Ramachandra TV, Bhat S, Mahapatra DM, Krishnadas G (2012) Impact of indiscriminate disposal of untreated effluents from thermal power plant on water resources. Indian J Environ Prot 32(9):705–718
Ramachandra TV, Mahapatra DM, Samantray S, Joshi NV (2013) Biofuel from urban wastewater: scope and challenges. Renew Sust Energ Rev 21:767–777
Ramachandra TV, Mahapatra DM, Bhat SP, Asulabha KS, Varghese S, Aithal BH (2014) Integrated wetlands ecosystem: sustainable model to mitigate water crisis in Bangalore (2014), ENVIS Technical Report-76. Environmental Information System, CES, IISc, Bangalore

Ramachandra TV, Mahapatra DM, Bhat SP, Joshi NV (2015) Biofuel production along with remediation of sewage water through algae. In: Algae and environmental sustainability, developments in applied phycology, vol 7. Springer, New Delhi, pp 33–51

Ramachandra TV, Vinay S, Mahapatra DM, Varghese S, Aithal BH (2016) Water situation in Bengaluru, ENVIS Technical Report 114. Environmental information system, CES, Indian Institute of Science, Bangalore 560012

Ramachandra TV, Mahapatra DM, Asulabha KS, Varghese S (2017a) Foaming or algal bloom in water bodies of India: remedial measures – restrict phosphate (P) based detergents, ENVIS Technical Report 108. Environmental Information System, CES, Indian Institute of Science, Bangalore 560012

Ramachandra TV, Mahapatra DM, Vinay S, Varghese S, Asulabha KS, Bhat SP, Aithal BH (2017b) Bellandur and Varthur Lakes rejuvenation blueprint, ENVIS Technical Report 116. Environmental Information System, CES, Indian Institute of Science, Bangalore 560012

Ramachandra TV, Vinay S, Asulabha KS, Varghese S, Bhat SP, Mahapatra DM, Aithal BH (2017c) Rejuvenation blueprint for lakes in Vrishabhavathi Valley, ENVIS technical report 122. Environmental Information System, CES, Indian Institute of Science, Bangalore 560012

Sforza E, Calvaruso C, Rocca N, Bertucco A (2018) Luxury uptake of phosphorus in *Nannochloropsis salina*: effect of P concentration and light on P uptake in batch and continuous cultures. Biochem Eng J 134:68–79

Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA (2013) Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus 2:587–600

Shilton AN, Powell N, Guieysse B (2012) Plant based phosphorus recovery from wastewater via algae and macrophytes. Curr Opin Biotechnol 23:884–889

Spohn M, Widdig M (2017) Turnover of carbon and phosphorus in the microbial biomass depending on phosphorus availability. Soil Biol Biochem 113:53–59

Srinivasan R, Yandigeri MS, Kashyap S, Alagawadi AR (2012) Effect of salt on survival and P-solubilization potential of phosphate solubilizing microorganisms from salt affected soils. Saudi J Biol Sci 19:427–434

Turner BL, Cheesman AW, Condron LM, Reitzel K, Richardson AE (2015) Introduction to the special issue: developments in soil organic phosphorus cycling in natural and agricultural ecosystems. Geoderma 257:1–3

Wu J, Huang M, Xiao H, Su Y, Tong C, Huang D et al (2007) Dynamics in microbial immobilization and transformations of phosphorus in highly weathered subtropical soil following organic amendments. Plant Soil 290:333–342

Xu M, Zhang W, Huang S (2015) Soil fertility evolution in China, 2nd edn. Chinese Agricultural Science and Technology Press, Beijing

Yuan Z, Pratt S, Batstone DJ (2012) Phosphorus recovery from wastewater via algae and macrophytes. Curr Opin Biotechnol 23:878–883

2 Site Specific Nutrient Management Through Nutrient Decision Support Tools for Sustainable Crop Production and Soil Health

Shiveshwar Pratap Singh

Abstract

The depletion of native nutrient reserves and emergence of multi-nutrient deficiencies are resulting in decline in factor productivity. Imbalanced use of fertilizers further aggravates the nutrient deficiency, proves uneconomic and environmentally unsafe. Site Specific Nutrient Management (SSNM) is an approach to provide the need based nutrients to the crops when needed. The SSNM provides the guidelines for dynamically adjusting fertilizer application as per local conditions. The main goal of SSNM through balanced and timely fertilizer use is to increase the crop yield, profit and to sustain the soil productivity. Different kind of tools like Crop Manager (CM), Nutrient Expert (NE) and GreenSeeker are available for SSNM. The CM and NE are nutrient decision support tools and recommend the nutrients for the cereals based answers of some questions by the farmers and yield target. GreenSeeker is a hand-held optical sensor that measures crop reflectance to calculate the normalized difference vegetation index (NDVI). This handheld sensor is used to assess nitrogen need of the crop, which allows for efficient fertilizer N management. Therefore, the adoption of SSNM not only helps in achieving the targeted yield but also improves the soil health.

Keywords

SSNM · Decision support tool · Crop Manager · Nutrient Expert · GreenSeeker

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2.1 Introduction

To feed the increasing world population, the demand of crop production with limited land area is increasing. In general, the yield of cereals is only 40–60% of their potential yield, mostly because nutrient management does not consider the crops' dynamic response to the environment. Thus intensification will need nutrient management that not only produces high yield but also maintains the soil quality and protect the environment. The adverse effects of the applications of plant nutrients, both at low and high levels of input could be prevented by effective management practices. This can be achieved through balanced fertilization such as Site Specific Nutrient Management (SSNM), combined with other practices (improved crop varieties, plant protection and water management) that stimulate the uptake of plant nutrients by the crop. The widespread occurrence of multi-nutrient deficiencies has changed the scope and content of balanced fertilization. There are no fixed guidelines available for balanced fertilization of crops or soil. It is crop and site specific; hence, the focus on SSNM is increasing.

The site-specific nutrient management approach has been developed by Kasetsart University and applied in various national and international projects over the last several years (Attanandana et al. 1999). It is a set of nutrient management principles, which aims to supply the nutrient to a crop for a specific field or growing environment (Majumdar et al. 2012; Jat et al. 2016). Site-specific nutrient management (SSNM), a plant-based approach, helps the growers for balanced application of essential nutrients to their crops. The optimal supply of nutrients to the crops could vary from field-to-field depending on crop and soil management, historical use of fertilizers, management of crop residues and organic materials, and crop cultivar. Hence, SSNM provides the guidelines for nutrient management practices to a specific field conditions.

Site specific nutrient management (SSNM) along with good crop management practices will help the farmers to achieve high yield and profitability. The principles of SSNM are general and could be applicable to other crops including rice. The SSNM provides the guidelines for 4R nutrient stewardship i.e., application of the right nutrient source, at the right rate, at the right time and in the right place to fill the deficit between the nutrient needs of high yielder crops and the supply of nutrients from indigenous sources, including soil, crop residues, manures and irrigation water.

Several workers have reported that by applying SSNM, the system productivity, economics and soil health was found to enhance (Jat et al. 2018; Satyanarayana et al. 2014; Dutta et al. 2014). SSNM enhanced the system productivity, water use efficiency and net returns by 13.4, 13.3 and 15.3% with respect to farmers practice, respectively in North-West Indo-*Gangetic* plains of India (Jat et al. 2018).

2.2 Concept of SSNM

Management of nutrient and recommendations in India is still based on response data arranged over large domains. The SSNM provides a guide for need based nutrition to the crops while recognizing the soil inherent capacity and spatial variability.

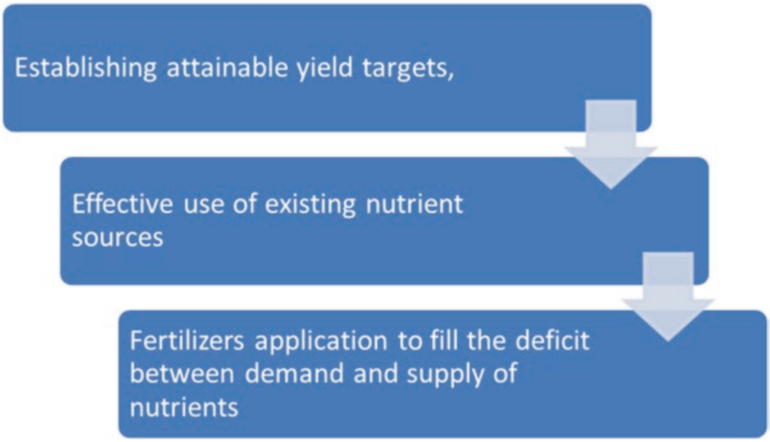

Fig. 2.1 Steps involved in SSNM approach

SSNM involves monitoring of all the pathways of plant nutrient supply, and calls for judicious combination of fertilizers, organic manures, bio-fertilizers, crop residues and nutrient efficient genotypes to sustain agricultural productivity. It avoids indiscriminate use of fertilizers and enables the growers to dynamically adjust the fertilizer use to fill the deficit optimally between nutrient needs of the variety and nutrient supply from natural resources like organic sources, irrigation water etc. It aims at nutrient supply at optimal rates and time to achieve high yield and efficiency of nutrient use by the crop.

There are three steps involved in SSNM approach as depicted in Fig. 2.1.

To develop the site specific integrated plant nutrient supply system, besides assessment of resource quality and socio-economic background of the farmers, soil nutrient supply potential and its spatial variability, productivity potential and yield targets for crops and cropping systems, estimation of nutrient requirements, and fertilizer use efficiency are essential.

2.3 Strategies of SSNM

The conventional approach to develop fertilizer recommendation is based on the response functions derived from the trials conducted at different locations. A key problem in these is that the nutrient interactions at higher yield levels is less understood particularly the relationship between plant uptake and the internal nutrient efficiencies. The core of SSNM approach is formed by the model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) developed by Janssen et al. (1990). The model described in four steps (i) the relationship between macro nutrients in above ground plant dry matter at physiological maturity, (ii) potential nutrient supplies from indigenous and fertilizer sources, (iii) grain yield and (iv) plant nutrient accumulation acknowledging interaction between NPK (major nutrients) (Mishra 2007). The model has been used to calculate the crop response to fertilizer application and to evaluate the fertilizer requirement to achieve target yield in rice, wheat and maize crops. The model can be applicable to other crops once the basic relations between grain yield and nutrient supply are known.

Components of SSNM (Mishra 2007).

2.3.1 Establishment of Attainable Target Grain Yield

The crop yield is location and season specific and depending upon climate, cultivar and management practices. The targeted yield for a specific location and season is the estimated grain yield obtained with crop management without any nutrient (NPK) constraints. The amount of nutrients taken up by a crop is directly related to yield. Therefore, the yield target indicates the total amount of nutrients that must be taken up by the crop.

2.3.2 Estimation of NPK Requirement for the Target Grain Yield

At the target grain yield, the nutrient requirement by the harvested crop is estimated from optimal internal efficiencies at balanced nutrition. As the target yield nears the potential yield the relationship of the grain yield and plant nutrients becomes curvilinear and internal efficiency decreases from standard optimal values.

2.3.2.1 Determination of Indigenous Nutrient Supply

The indigenous nutrient supply is the quantity of the nutrient supplied to the plant from soil, organic amendments, crop residues, manure and irrigation water i.e. other than fertilizer. The nutrient uptake from indigenous sources can be estimated from the nutrient-limited yield, which is the grain yield for a crop under the nutrient omitted plot i.e. not fertilized with a nutrient of interest but fertilized with other nutrients.

2.3.2.2 Calculation of Fertilizer (NPK) Rates

The requirement of fertilizer is determined by the deficit between the total nutrients needs by the crop (as determined by the yield target) and the indigenous supply of these nutrients (as determined by the nutrient-limited yield).

2.3.2.3 Use of Dynamic Nutrient Management

The rate and time of nitrogen application is predetermined at the time of start of season. The split application of nitrogenous fertilizer is generally made on the basis of crops' need as determined by leaf N status. The leaf colour chart (LCC) is a tool that can be used for assessing leaf N status and crops' need for nitrogen. All phosphatic fertilizers are applied near transplanting or sowing. The application of potassic fertilizers is generally made in two equal split doses i.e. 50% at transplanting or sowing and 50% at panicle initiation stage.

2.4 Tools for Site Specific Nutrient Management

The 'precision farming' is the need of time to obtain higher productivity and income in food production on small holdings. It can be achieved through information based decision making tools for a specific location and situation. A major aspect for such decision making is the site-specific nutrient management i.e. application of fertilizer in a particular location at the correct time and amounts.

Different kinds of tools have been developed by various organisations for SSNM.

1. Crop Manager/Nutrient Manager
2. Nutrient Expert
3. Green Seeker

2.4.1 Crop Manager/Nutrient Manager

The Nutrient Manager is nutrient decision support tool accessible through the web browser on computers and smartphones for nutrient recommendation to rice crop in irrigated or rainfed lowland environments, based on input from users, whether extension workers, crop advisors, or farmers. The Nutrient Manager for Rice: Philippines was released on CD in 2008, and starting in 2009 it was available on the Internet in English and five dialects of the Philippines (IRRI 2010a). A partnership of organizations in Indonesia similarly developed decision support software tailored to rice production for Indonesia. It was released on CD in Bahasa Indonesia with the title Pemupukan Padi Sawah Spesifik Lokasi (Location-Specific Rice Fertilization) in 2008 (Buresh 2010).

Nutrient Manager is developed by International Rice Research Institute (IRRI) Philippines. The internet-based versions have been or are being developed for many countries in Asia and Africa. A small farmer interacts with a voice recording in mobile phone applications that provides the information required to compute the nutrient management practices for his/her location and also provides the user-friendly text messages and/or images (GRiSP 2013).

The Nutrient manager is designed to help extension workers, farmers and other beneficiaries to quickly formulate fertilizer best management for rice crop. The tool consists of 10–15 questions i.e. easily answered by the farmer. On the basis of responses to the questions, the fertilizer guidelines with fertilizer dose required by crop growth stages is provided for the rice field. The timing and rate of fertilizer are adjusted on the basis of use of organic sources of nutrients by the farmers. With the help of this tool the fertilizer recommendations could be made for transplanted and direct-seeded rice, including inbred and hybrid varieties with a range of growth durations. These tools help farmers to increase their yield and profit by applying the right amount of nutrients at the right time. Based on the experiences of the Philippines and Indonesia with rice, it is now being replicated across Asia with rice, maize, and wheat (Buresh 2010; IRRI, 2010b).

Now, IRRI has developed the Crop Manager for Rice-based Systems (CMRS) with Nutrient Manager as one of its component. The guidelines for nutrient management in CMRS is based on site-specific nutrient management (SSNM) principles, as developed for rice through partnerships of IRRI with national agricultural research organizations in Asia. The *Nutrient Manager for Rice* developed by IRRI in 2008–2010 and the more recent *Nutrient Manager for Cereal Systems* developed by IRRI provide the SSNM-based, nutrient management component in CMRS. The Rice Crop Manager (developed by IRRI during 2013) for the Philippines provided the skeleton for the crop management decision in the subsequent *Crop Manager for Stress-Tolerant Rice* (CMSTR), *Rice-Wheat Crop Manager* (RWCM), and *Rice-Maize Crop Manager* (RMCM) which are now combined in Crop Manager for Rice Based System. The main objective of Crop Manager is to increase the farmer's income and sustain the productivity of rice-based cropping systems. The Crop Manager is a computer and mobile phone based tools and provides nutrient management guideline for rice, maize, and wheat to the individual farmer. This tool is in operations/validations in the countries of Bangladesh, India, Indonesia, Philippines and Vietnam. On the basis of the answers by a farmer on farming practices, CMRS automatically generate a rice, wheat, or rabi maize management guideline aimed at increasing the farmer's net income (Source: http://webapps.irri.org/in/br/cmrs/).

The CMRS can be used by crop advisers, extension workers, input providers and services providers who interview a farmer and after the interview, the collected information could be saved in computer, smartphone, or tablet until the device is connected through a Web browser. The saved information is then transfer to the CMRS 'model' via the internet, which calculates and transmits a crop management guideline for rice, wheat or rabi maize in rice-based cropping systems very shortly. The crop management guideline is location and crop specific. The one page printout of the guidelines can then be provided to the farmers. It can also be used by the extension worker, input provider, or provider of services to advise the farmer on how to increase net income through improved crop management (http://webapps.irri.org/in/br/cmrs/).

2.4.2 Nutrient Expert

Nutrient Expert (NE), a nutrient decision support tool, is developed by International Plant Nutrition Institute (IPNI) following the principles of 4R Nutrient Stewardship and site specific nutrient management (SSNM). Nutrient Expert is interactive and rapidly provides crop and site specific nutrient recommendation in the presence or absence of soil testing data (Pampolino et al. 2012; Satyanarayana et al. 2014; Dutta et al. 2014, http://software.ipni.net/article/nutrient-expert). Nutrient Expert predicts the attainable yield and yield response to the fertilizer from site information using decision rules developed from on-farm trials (Pampolino et al. 2014). It uses

(i) Characteristics of the growing environment like water availability and any occurrence of yield limiting constraints such as flooding, drought etc.

(ii) Soil fertility indicators like soil texture soil colour and organic matter content, soil test for P or K (if any), historical use of organic materials (if any), problem soils (if any)
(iii) Crop sequence in the farmers' cropping pattern
(iv) Crop residue management and fertilizers input
(v) Field current yields

The development of NE is done through collaboration with crop advisors from both public and private sectors, as well with scientists and extension specialists to ensure that NE meets users' needs and preferences, thereby increasing the likelihood and its adoption. Collaboration is carried out through a series of dialogues, consultations and partnerships towards collection of locally available agronomic data and information, integration of local users' preferences such as use of local language, measurement units, locally available fertilizer sources etc. and field testing, evaluation and refinement of the NE software. There is option for inclusion of locally available nutrient sources with farmers and accordingly the NE provides the nutrient recommendations for the crops and also calculates the profit (Figs. 2.2 and 2.3).

The detailed information about the various aspects of NE on different crops at different locations is compiled by IPNI and it could be downloaded for further reading by the link at http://www.ipni.net/publication/bca.nsf/issue/BC-SA-2014-1. The yield response to fertiliser application is a function of indigenous nutrient supplying capacity of soil and is determined from soil characteristics (i.e. colour, texture, and organic matter content), use of organic inputs (if any), and apparent nutrient balance (for P and K) from the previous crop. In the Nutrient Expert, the algorithms involved are so meticulous that it captures the required information through logical questions and predicts the yield responses close to the actual yield

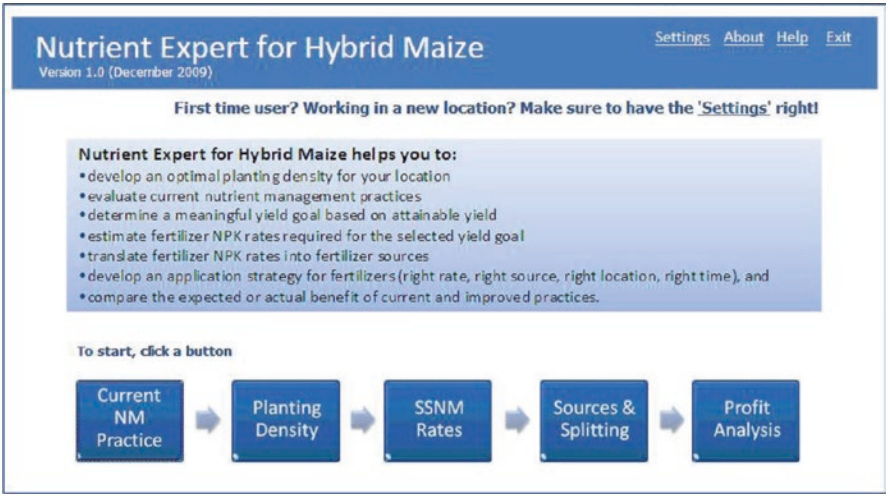

Fig. 2.2 Home section of Nutrient Expert for maize. (Source: Pampolino et al. 2009)

Name and/or location: Here; Site A **Field size:** 1 ha

Current yield: 110 cavan (FW) 5.3 t/ha (15.5% MC)

Growing environment: Favorable rainfed

Recommended altemative practice for hybrid maize

Yield goal: 165 cavan (FW) 8.0 t/ha (15.5% MC)

Planting density: 69,444 plants/ha

Distance between rows: 60 cm **Distance between plants:** 24 cm

Growth stage	Days after planting	Soil moisture	Fertilizer sources	Weight of full bag (kg)	Amount (bags)
Basal	0	sufficient	14-14-14	50	6.5
			Urea	50	0
			MOP	50	0.5
V6	25	sufficient	Urea	50	2.5
V10	35	sufficient	Urea	50	2

Other sources of nutrients: Fertilizer rates are adjusted to field size

Crop residue: high

Organic fertilizer: 0 t

Fig. 2.3 Fertilizer guideline for a favorable rainfed environment with locally-available fertilizers. (Source: Pampolino et al. 2009)

responses (Pampolino et al. 2014; Satyanarayana et al. 2014; Dutta et al. 2014). The NE-estimated yield responses compared with that of actual yield responses (Fig. 2.4) showed 16% higher N response, 31% lower P_2O_5 response and 29% lower K_2O response over the actual responses observed through omission plot techniques in different states of India. The yield response estimated with NE over the actual yield response observed from limited number of omission plot experiments indicated that NE is capable of capturing the temporal variability of nutrient requirement across the seasons along with considering the spatial variability between farmers' fields. Also, NE estimates yield responses based on sound scientific principles even in the absence of soil testing and forms the basis for generating fertiliser recommendations (Satyanarayana et al. 2014).

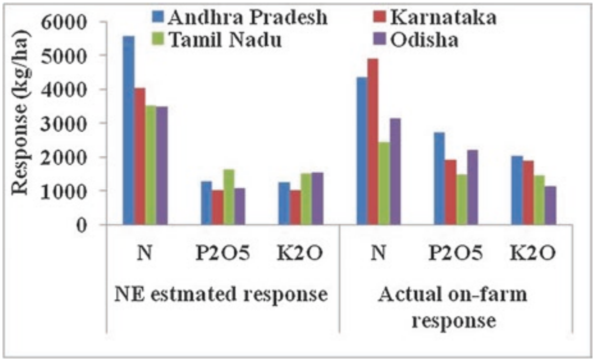

Fig. 2.4 The Nutrient Expert (NE) estimated yield responses and the actual on-farm responses in different regions of India. (Source: Satyanarayana et al. 2014)

2.4.3 GreenSeeker

The Crop Manager and Nutrient Expert suggest the NPK management as a whole but some other tools like GreenSeeker is used for N management only based on relative greenes of the leaves.

The farmers are generally applying higher amounts of nitrogenous fertilizer than the general recommendation to ensure high yields. However, the application of N fertilizer more or less than the actual need by the crop depends on spatial and temporal variability thereby reducing fertilizer use efficiency (Ali et al. 2018). Sensor-based strategies for nitrogen (N) management are promising to enhance the nitrogen use efficiency and to reduce the amount of N wasted to the environment (Ali et al. 2018). The GreenSeeker is a hand-held optical sensor (NTech Industries, Ukiah, CA.) i.e. developed by Oklahoma State University, senses a 0.6 × 0.01 m area when held at a distance of approximately 0.6–1.0 m from the illuminated surface (Arnall et al. 2006). The sensed dimensions remain approximately constant over the height range of the sensor. The GreenSeeker measures the fraction of emitted light in the sensed area that is returned to the sensor. The algorithm currently used by N-Tech Industries, "WheatN1.0," includes several distinct components (Arnall et al. 2006; Bushong et al. 2018). According to Raun et al. (2005) reported three components viz. (i) the prediction of grain yield during mid-season i.e. determined by dividing normalized difference vegetative index (NDVI) by number of days from planting to sensing, (ii) assessment of temporally dependent responsiveness to applied N by placing non-N-limiting strips in production fields each year, and comparing these to the farmers' practice i.e. fertilizer response index and iii) estimation of the spatial variability within each 0.4 m^2 area by using the coefficient of variation (CV) from NDVI readings.

The fertilizer N use efficiency could be enhanced by applying the soil test based recommended optimized N rate with the help of GreenSeeker, a device that measures crop reflectance to calculate the normalized difference vegetation index (NDVI). This handheld sensor is used to assess nitrogen need of the crop, which allows for efficient fertilizer N management. The NDVI is the fraction of the emitted visible red (RED, 650 ± 10 nm) and near-infrared (NIR, 770 ± 15 nm) radiation reflected back from the sensed area as it moves above the crop canopy at a height of 0.6–1.0 m, as depicted below (Oyeogbe et al. 2018; Ali et al. 2018)

NDVI = (NIR – RED)/(NIR + RED)Application of nitrogenous fertilizer based on optical sensor i.e. GreenSeeker increased grain yields of maize and wheat up to 20 and 14% (average of 2 years), respectively, compared to whole N application at sowing (Oyeogbe et al. 2018). Different studies on N management based on GreenSeeker showed the enhanced grain yield and nitrogen use efficiency (Raun et al. 2005; Arnall et al. 2006; Bushong et al. 2018; Oyeogbe et al. 2018; Ali et al. 2018).

2.5 Conclusion

Cultivation of high yielding varieties with unbalanced fertilization is causing multinutrient deficiencies and decrease in yield with poor quality. SSNM approach through different available tools could help in achieving the potential yield of the crops. One must follow the suitability and guidelines of the nutrient decision support tools before its use.

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References

Ali AM, Abou-Amer I, Ibrahim SM (2018) Using GreenSeeker active optical sensor for optimizing maize nitrogen fertilization in calcareous soils of Egypt. Arch Agron Soil Sci 64:1083–1093. https://doi.org/10.1080/03650340.2017.1411589

Arnall DB, Raun WR, Solie JB, Stone ML, Johnson GV, Girma K, Freeman KW, Teal RK, Martin KL (2006) Relationship between coefficient of variation measured by spectral reflectance and plant density at early growth stages in winter wheat. J Plant Nutr 29:1983–1997. https://doi.org/10.1080/01904160600927997

Attanandana T, Suwannarat C, Vearasilp T, Kongton S, Meesawat R, Boonamphol P, Soitong K, Charoensaksiri A (1999) Nitrogen fertilizer recommendation for grain yield of corn using a modeling approach. Thai J Agric Sci 32:73–83

Buresh RJ (2010) World congress of soil science, soil solutions for a changing world 1–6 August 2010, Brisbane, Australia. Published on DVD, pp 164–167. https://www.iuss.org/19th%20WCSS/Symposium/pdf/0792.pdf

Bushong JT, Mullock JL, Arnall DB, Raun WR (2018) Effect of nitrogen fertilizer source on corn (Zea mays L.) optical sensor response index values in a rain-fed environment. J Plant Nutr. https://doi.org/10.1080/01904167.2018.1434202

Dutta SK, Majumda K, Shahi V, Kumar A, Kumar V, Gupta N, Satyanarayana T, Jat ML, Pampolino M, Johnston A (2014) Nutrient Expert-wheat: a tool for increasing crop yields and farm profit. Better Crops-South Asia 8(1):11–13

GRiSP (Global Rice Science Partnership) (2013) Rice almanac, 4th edn. International Rice Research Institute, Los Baños, 283p

IRRI (International Rice Research Institute) (2010a) Nutrient manager for rice. www.irri.org/nmrice

IRRI (International Rice Research Institute) (2010b) Site-specific nutrient management. www.irri.org/ssnm

Janssen BH, Giking FCT, van der Eijk D, Smaling EMA, Wolf J, van Reuler H (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299–318

Jat HS, Jat RK, Sing Y, Parihar CM, Jat SL, Tetarwal JP, Sidhu HS, Jat ML (2016) Nitrogen management under conservation agriculture in cereal-based systems. Indian J Fert 12:76–91

Jat RD, Jat HS, Nanwal RK, Yadav AK, Bana A, Choudhary KM, Kakraliya SK, Sutaliya JM, Sapkota TB, Jat ML (2018) Conservation agriculture and precision nutrient management practices in maize-wheat system: effects on crop and water productivity and economic profitability. Field Crop Res 222:111–120

Majumdar K, Jat ML, Shahi VB (2012) Effect of spatial and temporal variability in cropping seasons and tillage practices on maize yield responses in eastern India. Better Crops-South Asia 6:4–6

Mishra B (2007) Site-specific Nutrient Management for sustainable crop production. In: Mishra B, Chandra R, Singh SK (eds) Management of soil quality for sustainable agriculture. Satish Serial Publishing House, Delhi, pp 233–239

Oyeogbe AI, Das TK, Bandyopadhyay KK (2018) Agronomic productivity, nitrogen fertilizer savings and soil organic carbon in conservation agriculture: efficient nitrogen and weed management in maize-wheat system. Arch Agron Soil Sci. https://doi.org/10.1080/03650340.2018.1446524

Pampolino M, Witt C, Pasuquin JM, Sinohin PJ (2009) Nutrient Expert for hybrid maize (version 1.0). A software for formulating fertilizer guidelines for tropical hybrid maize. International Plant Nutrition Institute, Penang

Pampolino MF, Witt C, Pasuquinet JM, Johnston A, Fisher MJ (2012) Development approach and evaluation of the Nutrient Expert software for nutrient management in cereal crops. Comput Electron Agric 88:103–110

Pampolino MF, Witt C, Pasuquin JM, Johnston A, Fisher MJ (2014) Development and evaluation of the Nutrient Expert decision support tool for cereal crops. Better Crops-South Asia 8(1):4–6

Raun WR, Solie JB, Stone ML, Martin KL, Freeman KW, Mullen RW, Zhang H, Schepers JS, Johnson GV (2005) Optical sensor based algorithm for crop nitrogen fertilization. Commun Soil Sci Plant Anal 36:2759–2781

Satyanarayana T, Majumdar K, Dutta S, Jat ML, Pattanayak SK, Biradar DP, Aladakatti YR, Pampolino M, Johnston A (2014) Nutrient Expert-maize: a tool for increasing crop yields and farm profit. Better Crops-South Asia 8(1):7–10

Carbon Sequestration for Soil Fertility Management: Microbiological Perspective

3

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Abstract

Carbon content in soils is a key parameter for soil health management and higher plant productivity sustainably. Total carbon in soil is accounted to be more than combined carbon in the vegetation and atmosphere; it contributes significantly to climate adaptation, biodiversity and nutrient recycling. These basic characteristics are essential for global food security, eco-friendly environment, and human welfare. The method of eliminating atmospheric CO_2 and its accumulation in the soil carbon pool known as carbon sequestration is primarily mediated by plants through the process of photosynthesis and respiration. Ultimately, dead animal and plant residues are decomposed by microbes through their saprophytic, mutual or pathogenic activities. Thus, microbes are the chief modulators of the terrestrial carbon cycle and regulate the net carbon storage or turnover rates in soil carbon sequestration (SCS). Recent studies are shading light on the major factors involved in the mechanism of SCS and their associations with soil-plant-microbe interactions. These factors mainly include soil properties (soil depth, type, pH, pore space, bulk density, and texture), climate parameters (temperature and precipitation) and land management practices (LMPs). This chapter summarizes the basic concept of carbon sequestration, forms of carbon (organic and

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inorganic), factors influencing the SCS and microbial activity, microbial communities associated with SCS and their potential in enhancing the soil carbon storage.

Keywords
Carbon sequestration · Soil-plant-microbial interactions · Soil microbial biomass · Soil fertility · Organic soil carbon · Priming effect

3.1 Introduction

All living organisms require a range of elements from the Earth, such as hydrogen (H), carbon (C), oxygen (O), nitrogen (N), sulfur (S), phosphorus (P) including some metal ions, for example, iron (Fe), nickel (Ni), copper (Cu), manganese (Mn), zinc (Zn), and molybdenum (Mo) etc. (Shelake et al. 2018). Among them, C is one of the most abundant elements in the Earth's crust and is the major building block of life on Earth. C is the primary constituent of biomolecules, including nucleic acids, proteins, carbohydrates, and lipids. In a nonliving environment, C can exist in many forms, predominately as plant biomass, soil organic matter, carbonate rocks, coal, petroleum, natural gas, carbon dioxide (CO_2) and dissolved in seawater. The C can remain deposited in soils for ages, or it can be quickly released back into the atmosphere. The C cycle is the transformation of C in diverse forms between the atmosphere, biosphere, and pedosphere (Orgiazzi et al. 2016).

Soil fertility is the capability of soil to provide a suitable environment for the plant growth including chemical, physical and biological requirements for higher productivity, reproduction and quality depending on climate, land use, plant, and soil type (Abbott and Murphy 2007). Maintenance of appropriate soil C concentration is vital to soil fertility, greenhouse gas (GHG) emission (especially CO_2), nutrient cycling and biodiversity. Soils include C in two forms, i.e., soil organic C (SOC) and soil inorganic C (SIC) that defined in Table 3.1 (Scharlemann et al. 2014). The SOC present as soil organic matter (SOM) is a vital factor in biogeochemical cycling of elements, and a key component for improving soil productivity in sustainable agriculture (Fang et al. 2018). In this context, soil microbes that can make use of both organic and inorganic C as an energy source greatly influence the soil C sequestration (SCS) by altering C turnover rates. (King 2011).

In this chapter, we discuss the basic concept of C sequestration, organic and inorganic forms of C, techniques, and factors influencing the SCS in relation to microbial activity, microbes involved in SCS and their potential in enhancing the soil C gain. Also, different approaches followed for soil fertility management affect the soil and plant microbiome thereby altering the microbial community in agricultural lands (Waghunde et al. 2017). In the following sections, we have summarized the consequences of land management practices (LMPs) on SCS by microbes.

Table 3.1 Terminologies used in carbon sequestration studies are summarized, and more details with references explained in the main text

Terminology	Description
Carbon cycle	Transformation of carbon in diverse forms between the atmosphere, biosphere, and pedosphere
Carbon sequestration	Removal and storage of carbon dioxide from the atmosphere, so that unable to contribute to global warming
Soil organic carbon	Soil organic matter that takes account of relatively available carbon as fresh plant remains (humus) and relatively inert carbon in materials (charcoal)
Soil inorganic carbon	Mineral forms of carbon produced from weathering of underlying geological material (parent material) or mineral reaction with CO_2 in the atmosphere
Bio-sequestration	The capture and storage of the carbon by biological processes.
Carbon sink	Carbon reservoir are natural or artificial bodies that capture and store it for longer periods
Mesovore	Soil-dwelling insects, worms, and nematodes
Priming effect	The stimulation or inhibition of microbial decomposition of soil organic matter by a fresh supply of organic substrates
Copiotrophs	Fast-growing bacteria that use labile carbon and mainly grow in nutrient-rich soil
Oligotrophs	Slow-growing bacteria that use recalcitrant carbon forms and grow in nutrient-poor soils

3.2 Carbon Sequestration

Carbon sequestration and C storage, these two terminologies being used alternatively leading to some confusion (Chenu et al. 2018). The C sequestration defines as the capture and storage (near-term or long-term) of C through biological and abiotic processes making it unavailable to contribute to global warming (Trivedi et al. 2013). The C sequestration results in the reduction of CO_2 concentration in the atmosphere (Lal 2008). The C storage is a broader term which includes the enrichment of C stocks over time from the atmosphere at the specific land unit. Consequently, storage may not relate to a net fixation rate of atmospheric CO_2. The sequestered C generally stored in vegetation (mostly forests), soils, oceans, and geologic formations. Even though oceans are the main storage house of C on the Earth, soils play a critical role in balancing the global C cycle.

Soils consist of the world's largest stock of SOC, approximately 75% of the total organic C pool on land (Mondal et al. 2017). Although long-term storage of organic C is preferable regarding GHG mitigation for reducing global warming, the ratio of labile and stable fractions of SOC is essential to maintaining soil fertility and soil biodiversity (Chenu et al. 2018). Therefore, the retention time of both labile and stable forms of C is a crucial parameter for the understanding status of soil fertility in agricultural lands.

3.2.1 Soil Carbon Sequestration (SCS)

The SCS defines as the practice of converting atmospheric CO_2 into the soil C (both SOC or SIC) using plants, plant parts and other suggested management practices that retains or store (short-term or long-term) C as a part of the SOM (humus) (Lal 2008; Olson et al. 2014). This method of eliminating atmospheric CO_2 and its accumulation in the soil C pool is primarily mediated by plants which assimilate C through the process of photosynthesis, and some of it returns to the atmosphere through respiration. The animals consume C as plant tissue and finally added to the soil after their death. Ultimately, dead residues of plant litter and animal are then decomposed by microbes and return to the global C cycle.

The SOC generally present as SOM while the SIC as elemental C and carbonate minerals such as calcite, dolomite, and gypsum (Lal 2004). The SIC is far less prone to lose than SOC. The C retention time depends upon the natural vegetation, soil texture, climatic conditions, and drainage. Microbes play a vital role in the biogeochemical cycle of SOC and SIC by sequestering and converting one form into another that can be reused by other biological systems (Gougoulias et al. 2014).

3.2.2 Soil Organic Carbon (SOC)

The SOC contain residues of plants and animals at different stages of decomposition including the microbial biomass and their byproducts. The SOC is the main constituent of SOM (45–60%) and refers only to the C component of organic compounds (Lal 2016). The SOC comprises a heterogeneous mixture of organic materials, for example, microbial cells, animal and plant residues, humus, charcoal, graphite, and coal. The SOC material varies in particle size, C content, turnover time and its decomposition rate. In many soils, the SOC estimated by considering all of the C stock as SOC except inorganic forms of soil C (FAO and ITPS 2015). The estimated SOC pool stores 1500 Pg C (1 Petagram equal to 10^{15} g) in the upper one-meter layer of soil which is more than the combined C present in the atmosphere and terrestrial vegetation (about 800 and 500 Pg respectively) (FAO and ITPS 2015). This phenomenal SOC reservoir is not stable, and there is a continuous trade-off between the different global C pools in diverse molecular forms (Kane 2015).

On the basis of physical and chemical stability, SOC classified into three different pools (Falloon and Smith 2000; O'Rourke et al. 2015):

(a) Active pool (also referred as a labile or fast pool; the decomposition will result in a large proportion of initial biomass loses in 1–2 years after the addition of fresh SOC).
(b) Intermediate pool (microbial processed and partially stabilized SOC with a turnover period of 10–100 years).

Table 3.2 Soil organic matter (SOM) fractions and their breakdown rates

SOC pools	SOM fraction and particle size	Description
Active pool	Plant residues (>2 mm)	It includes plant materials residing within the soil and on the surface with a turnover time of <5 years
Active pool	Particulate organic matter (2 mm–0.05 mm)	Partially decomposed organic material with a decomposition time of <100 years
Living pool	Soil microbial biomass (variable)	It includes bacteria and fungi with a turnover time of <3 years
Stable pool	Humus (<0.05 mm)	Well-decomposed organic material and decomposition takes <100–5000 years

(c) Stable pool (also referred as refractory or slow pool; a period of very slow turnover of 100 to >1000 years).

Additionally, stable SOC pool contains a pyrogenic form which subsequently produced during wildfires from the partially carbonized biomass (Schmidt and Noack 2000). Pyrogenic SOC contains highly condensed aromatic C compounds (black or pyrogenic C) that cannot be degraded by microbes and thus remain stable for a longer time in soils (Lehmann et al. 2015; Lefevre et al. 2017). The SOC divided into different SOM fractions according to the speed and ease of SOC availability from SOM fraction (Table 3.2). This classification is based on the size and rate of SOM breakdown into another form. Some SOC forms are highly reactive and involved in numerous pyogenic processes. The mean residence time (MRT) or the turnover rate depends on the degree of protection within the soil matrix (Dungait et al. 2012).

3.2.3 Soil Inorganic Carbon (SIC)

The SIC consists of mineral forms of C. These mineral forms produced through weathering or chemical reaction of soil minerals with atmospheric CO_2. The SIC consists of primary (lithogenic) and secondary (or pedogenic) carbonates. The primary carbonates are inherited from the parent material of the soil with no change in SIC content while the secondary carbonates are the products of the bicarbonates and carbonates reactions with Ca^{+2} or Mg^{+2} (Jansson et al. 2010; Lal 2016). The formation of secondary carbonates leads to the sequestration of atmospheric CO_2. The SIC is an important constituent in soils of arid, semi-arid or semi-humid regions. The relative proportions of SIC and SOC pool changes depending on soil type, water availability and climatic conditions, for example, roughly two to ten times more SIC storage reported in arid and semiarid regions than SOC (Batjes 2006). The SIC rate of accumulation is generally higher than that of SOC, and the SIC pools significantly change with different soil types, climatic variation, land use type, and atmospheric nutrient deposition (Wu et al. 2009).

3.3 Significance of Soil Carbon Sequestration (SCS) in Soil Fertility Management

The conventional farming practices have degraded much of the agricultural land. The C sink potential of cultivable and depleted soils is 50–66% of the historic C loss, i.e. about 42–78 gigatons (Lal 2004). As a result, the actual C storage potential of soil remains unexploited. To understand the real C storage potential of arable land the innovative and environment-friendly LMPs needed in agriculture.

Soil naturally absorbs a huge amount of C through microbial decomposition and can act as a C sink. Sequestering C in soil reduces the atmospheric CO_2 concentration with less impact on land and water, need for the lesser amount of energy and lower costs. The SCS, both as SOC and SIC possess numerous complementary profits such as food and nutritional security, reduced soil erosion, improved soil structure and soil quality for agriculture and plant microbiome. Balanced distribution of SOC and SIC facilitate the availability of plant-available water reservoirs leading to lesser need of irrigation, improved storage of plant nutrients, reduction of pollution, assistance in climate moderation, better economic and aesthetic value of soil, biodiversity conservation and enrichment, elemental recycling, etc. (Lal 2004, 2008). An appropriate amount of SOC in upper soil layers helps to maintain proper soil structure, healthier water and nutrient use efficiency and retention. It also enhances the plant immunity to abiotic stresses like drought (Banwart et al. 2014). The SOM fractions supply energy for the microbial community, and thus, the proportion of SOC in SOM fraction is directly linked with soil fertility (Lehman et al. 2015). SOC acts as a health indicator for soil because of its contributions to food production, GHG mitigation, climate adaptation, and significance in water availability for plants and water storage (Trivedi et al. 2018).

3.4 SCS Status in Global and Indian Soils

The soil is the biggest C pool terrestrial global ecosystem, and it holds approximately three times more C than that of the atmosphere. Therefore, a little deviation in global C stock can cause significant modifications in atmospheric CO_2 concentrations (Scharlemann et al. 2014). India has diverse climatic zones, landforms and vegetation types, therefore, several soil types generated in different regions of India. Indian soils are classified into different orders by their nature and characteristics by National Bureau of Soil Survey and the Land Use Planning (NBSS and LUP) using the standards defined by USDA soil taxonomy to make it equivalent at the international level.

The SCS is of global significance since it plays a major role in GHG mitigation and the global C cycle in the ecosystem. To develop suitable management practices for SOC sequestration, basic information about SOC and SIC stocks in the specific land unit is essential (Pal et al. 2015). The estimates of C stocks in seven soil orders (*Entisols*, *Alfisols*, *Inceptisols*, *Aridisols*, *Ultisols*, *Vertisols*, *Mollisols*) suggest that the SOC and SIC stocks are variable in Indian soils depending on the soil depth and climatic conditions (Bhattacharyya et al. 2000). For example, SOC stock is less than that of SIC in the top Indian soils (0–150 cm), however, in case of five bio-climatic zones of India (cold arid, hot arid, semi-arid, sub-humid, Humid to per-humid, coastal), SOC availability is two times higher than SIC (0–30 cm). Overall, in all the soil orders, the concentration of SIC increases with soil depth, excluding Ultisols. These data indicate that climatic condition influences the ratios of SOC and SIC in Indian soils (Pal et al. 2015).

3.5 Factors Influencing Interactions Between SCS, Soil Fertility and Microbes

There is a multitude of factors affecting SCS, soil fertility and microbial populations in the soil. These factors mainly comprise soil properties (soil type and depth; soil texture; soil pH; composition of soil minerals), climate conditions (temperature and precipitation), and land use and LMPs. Some of these factors are discussed in following sections in relation to SOC because of their direct role in soil fertility and on microbial population.

3.5.1 Soil Properties

3.5.1.1 Soil Type and Soil Depth

The SOC level differs with soil type and soil depth. The SOC content generally reduces with increase in soil depth. The SOC level is not the same in different soil orders, for example, highest in *Histosols* and lowest in *Aridosols* at the specific land unit (Eshwarn et al. 1993). The SOC and soil order correlation associated with the disparity in climate, soil mineral composition, LMPs and topography (Baldock and Skjemstad 1999). Unavailability of fresh SOC in deep layers, a necessary energy source for soil microbes, the stable SOC in deep soil layers remains undisturbed (Fontaine et al. 2007). Therefore, without fresh SOC supply, there will be no decomposition of the SOC pool in deep soil layers even after fluctuations in temperature at upper soil layer or in the atmosphere.

3.5.1.2 Soil Texture

Soil texture directly alters the soil C stocks. It controls the SOC storage in the soil and the net mineralization of SOM. The rate of SOM decomposition in sandy soils is quicker than clay type soils. Clay soils accrue C at faster rates while sandy soils may build up almost no C stocks, even after several years (Christensen 1996). Soil C stock considerably increases with the increase in the amount of soil clay (Follett et al. 2012). The correlation between higher clay contents and increased SOC is associated with augmented soil stability and aggregation (Trivedi et al. 2015). Soil aggregates commonly classified into by their size as (1) large mega (less than 250 μm), (2) macro (50–250 μm), and microaggregates (bigger than 50 μm) (Tiemann et al. 2015). The size of the soil aggregates increases with the more deposition of polysaccharide and clay layers on the soil surface. Soil clay content indirectly influences SOC storage because of higher aggregation occluding organic materials, making them inaccessible to microbes and their enzymes. The decomposition of humus (SOM) generally occurs in slower rates in silts and clays than in coarse soils increasing the MRT of SOC (Dalal and Chan 2001; Six et al. 2006).

3.5.1.3 Soil pH

Soil pH determines the acidity or alkalinity of a soil solution and mediated by both acid and base forming cations present in the soil. The most favorable pH for a faster rate of SOM mineralization is about 6.7, suggestive of both hydrogen and hydroxyl ions can hamper microbial respiration. Liming acid soils speed up the SOM decomposition by microbes due to the altered concentration of ions, thus changing the stored SOC amount in the soil. In a natural ecosystem, SOC amount increases at soil surface due to higher microbial activity, furthermore, reduction in soil pH decreases the soil microbial activity and vice versa (Dalal and Chan 2001).

3.5.1.4 Composition of Soil Minerals

The composition of soil minerals is decisive in the total amount of SOC storage, SOC retention time, and C fluxes in the natural ecosystem during the process of long-term soil development (Torn et al. 1997). The availability of multivalent cations, for instance, minerals containing calcium (Ca), amorphous aluminum (Al) or iron (Fe) safeguards the SOC from microbial degradation by the process of aggregation and adsorption through clay-SOM complexes and cation bonding (Oades 1995; Krull et al. 2001).

A more stable fraction of humus partitioned into two types depending on the level of decomposition: The first is the active part that is still subject to further decomposition, and the other is highly stable, insoluble form as passive humus (or recalcitrant C). Active humus is an excellent source of plant nutrients (nitrates and phosphates), while passive humus is important for soil physical structure, water retention, and tilth.

3.5.1.5 Other Soil Properties

The soil properties that affect the SOC mineralization consists of pore space, bulk density, and pore size (Baldock and Skjemstad 1999). These soil properties change the water and oxygen availability for microbes. The microbial activity is maximized in soil with water-filled pore space about 50–75%. Pore space mainly regulates the microbial activity by altering soil texture and SOM content (Hudson 1994). The soil aeration and microbial respiration also controlled by the total soil bulk density or soil porosity. Soil bulk density of 1.0 is considered appropriate for maximized microbial activity for SOM accumulation, and bulk density of about 1.2 is best for microbe-mediated SOM mineralization (Hudson 1994).

3.5.2 Climate Conditions

3.5.2.1 Mean Annual Temperature

Temperature directly influences the SOC decomposition rate, and previous studies suggested that it is more rapid in tropical regions. The SOC decreases with an increase in mean annual temperature, and it is attributed to the enhanced microbial activity and SOM decomposition rates (Lloyd and Taylor 1994; Dalal and Chan 2001). The warm and moist environment support microbial growth and activity causing lesser accumulation of SOC in soils compared to colder climates. As a result, the soils in hot climates hold less SOC than in cold climates (Canadell et al. 2007).

3.5.2.2 Soil Moisture and Mean Annual Precipitation (MAP)

Soil moisture affects the C exchange between the ecosystem and SOM (Yuste et al. 2007; Xia and Wan 2012). Higher moisture content alters the physical properties (gas and solute diffusion and water movement) and also influences the microbial activity. Water accessibility and mean annual precipitation (MAP) can change C input to the soil by monitoring plant growth and net productivity in agriculture (Weltzin et al. 2003). Conversely, some studies suggested MAP did not extensively change the SOC (Follett et al. 2012). Recent studies support the notion that an increase in SOC associated with the increased MAP. For example, Changes in MAP alters the carbohydrate degradation potential of a bacterial community that directly affects the SOC sequestration (Martiny et al. 2017).

3.5.2.3 Land Management Practices (LMPs)

The removal of vegetation covers causes an increase in the rate of SOC decomposition due to a change in soil moisture and temperature regimes. Human activities in the last 150 years have led to the depletion of SOC and the exacerbation of global warming and GHG emission (Ontl and Schulte 2012). The conventional agricultural practices causing SOC loss comprise biomass burning, tillage and soil disturbance, deforestation, draining of wetlands, and uncontrolled grazing. Emission of these harmful gases from agricultural practices affected the agricultural ecosystem.

The SOC is a sign of the net balance of organic C inputs and losses in the soil. The agricultural management practices that improve C input (application of animal manure, biosolids, and compost) or reduce C losses can increase soil C storage (Lorenz et al. 2007). Altered agricultural practices that enhance the fresh SOC availability at the variable soil depth could stimulate the SOC loss which is buried deep in the soil (Fontaine et al. 2007). The management technique that increases SOC storage includes crop rotation, pasture, and grazing management, management to increase crop yields, management of tillage and crop residues, application of organic matter and alternative farming systems, etc. Any management practice that alters the microbial activity has the potential to affect the amounts of SOC at the specific land unit. The LMP accelerates the rate of decomposition of SOC through soil microorganisms by regulating the organic matter availability. As compared to tillage, minimum or no tillage with residue retention has shown higher potential to maintain and or reintroduce C into soils (Allmaras et al. 2000; Baker et al. 2007).

3.6 Soil Microbes Involved in Carbon Sequestration and Crop Productivity

Soil microbes play a vital role in the SCS and are key components in the advancement towards healthy soil structure for agriculture. Soil microorganisms are the major contributors to the total C budgets of the ecosystem through their several activities such as decomposition, symbiotic or pathogenic interaction with plants, thereby altering nutrient availability, storage, and maintenance of fixed C in soil (Trivedi et al. 2016). Soil microbes play dual functional roles as components of SOC as well as producers of SOC. Microbes decompose plant remains into C molecules that are protected and sequestered by inhibiting their immediate release into the atmosphere (Six et al. 2006). The microbial contribution to SCS is directly related to the interactions between the microbial community, the amount of microbial biomass, microbial by-products and soil properties (discussed earlier in the above sections).

Several groups of soil microbes facilitate micro-aggregate formation and stabilization that improves the SCS in soil (Woodward et al. 2009; Lennon et al. 2012). The aggregate stability is directly proportional to C input, and it enhances with the increase of C input (Mummey et al. 2006). The SOC improves the fertility and water-retaining capacity of the soil. There is a huge diversity of microorganisms present in the soil, but little information available about their role in stabilization of C. Also, mesovores (defined in Table 3.1) transform bigger plant residues into smaller ones that metabolized by microbes like fungi and bacteria. A variety of C types (differing in size and complexity) generate during the decomposition pathway associated with silt-clay particles and integrated into soil aggregates. (Grandy and Neff 2008; Grandy and Wickings 2010).

Rhizosphere priming is one of the important concepts that alter the nutrient availability and substrate quality for plant and microbial growth (Murphy et al. 2015). Priming effect is the stimulation or inhibition of microbial decomposition of SOC by a fresh supply of organic substrates, for example, root exudation of organic components or fresh plant litter (Kuzyakov et al. 2000; Kuzyakov and Blagodatskaya 2015). Root exudation is one of the main sources of available C to microbes through C input from plant to soil (Luo et al. 2014). Soil microbial activities produce labile C by litter decomposition that conversely alters the nutrient availability back to plants. This interactive effect is regulated by P and N availability (Dijkstra et al. 2013). There is usually some leftover organic material during the metabolic processes of plant and microbes, which contain C, nitrogen, and minerals. This remaining SOM is sequestered and stored as SOC and SIC.

3.6.1 Fungi

Fungi usually grow as long thread-like structures called hyphae. Soil fungi can categorize into three groups- decomposers (saprophytic), mutualists and pathogens or parasites. The decomposing fungi transform dead organic material into fungal biomass, CO_2, and small molecules, like organic acids. This process is of prime importance in immobilizing and retaining nutrients in the soil. The organic acids produced by fungi assist in increasing the build-up of humic-acid rich organic matter that is less prone to degradation. Mutualistic fungi such as mycorrhiza form symbiotic associations and colonize plant roots which are most common. This symbiotic interaction found in about 80% of plant species and every habitat in the ecosystem (Smith and Read 2008). The pathogens are the third group of fungi responsible for plant diseases leading to weakened growth or death of the plant.

Soil fungi play an important part in SCS by producing glomalin-like compounds that help in soil aggregate formation and maximize the total C stored in soil (Rillig 2004). Vesicular-arbuscular mycorrhiza (VAM) receives simple sugars from plants and provides nutrients to the partner-plants leading to faster plant-growth (Govindarajulu et al. 2005; Hoeksema et al. 2010) and VAM species reported to actively supports the soil aggregation and C levels using isotopic and molecular techniques (Clemmensen et al. 2013). Also, fungi utilize CO_2 removed from the atmosphere by plants to build hyphae. Some melanin-containing fungal hyphae-like *Aspergillus phoenicis* increases the polyaromatic and biopolymeric C in soil micro-aggregates. As a consequence, it improves the SOC retention time (Schreiner et al. 2014). Some C compounds produced by fungi and other microbes show longer retention time in the soil in comparison to that of the plants (Prescott 2010).

3.6.2 Bacteria

Soil bacteria divided into two ecological functional groups categorized soil microbes on the basis of their trophic lifestyles and C-use potential, copiotrophs (Bacteroidetes, class α, and γ Proteobacteria) and oligotrophs (Actinobacteria, Acidobacteria, and class Deltaproteobacteria) (Fierer et al. 2007). Copiotrophs are the fast-growing bacteria that use labile C and mainly grow in nutrient-rich soil. While oligotrophs are the slow-growing bacteria that use recalcitrant C forms and grows in nutrient-poor soils. Oligotroph-dominant soils have lower C turnover rates leading to less CO_2 emissions and higher SCS (Singh et al. 2010). The copiotroph-dominant soil possesses more soil C because they consume more labile forms over recalcitrant organic C (Fierer et al. 2012). A recent study by Finn et al. (2017) described the correlation between LMPs and preference of particular microbial community (i.e., copiotrophs) suggesting that the changes in soil microbial community that reduce SOC loss through LMPs can support the retention of elevated SOC stocks in agricultural soils.

3.6.3 Fungal and Bacterial Ratios

Bacteria and fungi both play distinctive roles in SCS because of their inherent stoichiometry, particularly N and C. The average C to nitrogen ratio in bacteria and fungi is around 4 and 10, respectively (Six et al. 2006). The soil population ratio of fungi to bacteria shows a relationship with SCS potential. Consequently, higher fungal biomass correlated with greater C storage in soils due to relatively higher C use efficiency by fungi (Strickland and Rousk 2010) which are further regulated by the methods selected for of LMPs. The exact mechanism about relatively higher C accumulation rates in fungal biomass needs direct experimental evidence at field level (Strickland and Rousk 2010; Trivedi et al. 2018).

3.7 Approaches for Improved SOC Sequestration and Soil Fertility

Conservation of terrestrial C pool accumulated over millennia should be a most important priority, as it offers the cost-friendly opportunity for reduced GHG emission and sustainable ecosystem (Schulte et al. 2014). Sustainable LMPs are an alternative option in place of conventional agricultural practices which causes GHG emissions from the soil to the atmosphere. The C sequestration and various recommended LMPs are correlated to soil fertility, tillage, grazing and forestry (Poulton et al. 2003).

Agricultural practices can affect the C sequestration by four ways: decreasing the level of soil disturbance (i.e., tillage) to enhance the physical protection of soil C in aggregates; increasing the mass and quality of plant and animal inputs to soils; improving soil microbial diversity and abundance, and maintaining continuous vegetation cover on soils. Modulation of the soil microbial community for SCS and agriculture is possible. Major challenges consist of the understanding genetics of C sequestration process in plant and microbes, identification of key species in C mobilization and storage, detailed knowledge about soil-plant-microbe interactions in the ecosystem, spatiotemporal effects of the plant-microbial population at a larger scale and longer periods (summarized in Trivedi et al. 2018). Some of these concepts discussed in the following paragraphs.

Forest and woodland ecosystems contain more C than pasture or arable ecosystems. In some cases, SOC levels in the most productive pastoral systems can match with the levels found in forest soils, arable soils generally less amount of SOC (Bolin et al. 2000). Mixed cropping systems with a combination of trees and arable plants (silvoarable or agroforestry) or trees and grass (silvopastoral systems) show some promising benefits of the forest to farmed land. Recent studies suggested that agroforestry and intercropped systems augment the C storage (Nair et al. 2009) which stimulate the nitrogen and C cycle on a loamy soil (Guo et al. 2009). Soil C in monocropping remains the same or declines over a longer period compared to mixed cropping systems (Skinner et al. 2006).

The growing perennial crops instead of annual ones may lead to gains in SOC enrichment through the higher activity of biodiversity of microbes. Also, perennial plants store more C than annual crops increasing the C retention time. Perennial crops are more efficient to intercept more of the sunlight and use it for photosynthesis (Glover et al. 2010). Even though long-living perennial crops have deep root systems which efficiently uptake the nutrients and water and add more C into the soil, there is a limit to its SCS potential. Therefore, the proper combination of perennial crops with recommended LMPs necessary for efficient SCS in agricultural soils.

The key plant traits influencing SOC sequestration (root depth, structure, and architecture; litter composition) are well-known. Characterization of genetic variations responsible for altered SOC sequestration in plant needed. Some early advancement has been made regarding mapping of genes in perennial ryegrass for C sequestration with effective C storage in the litter (Gill et al. 2006). Key questions to be resolved are the total SCS capacity of soil and finding the right equilibrium between below-ground and above-ground C in the plant.

Soil microbes and fungi release C compounds into the environment. While bacteria are relatively well studied, soil fungi are being studied recently in relation to SCS. Studies of SOM decomposition in lands have shown a critical role of phenolic compounds in inhibition of microbial enzymes (Zibilske and Bradford 2006; Toberman et al. 2008; Sinsabaugh 2010) suggesting a specific role of phenolic compounds in the C cycle.

Even though microbial association with turnover rates of SOC is well-known, experimental data of direct SCS regulation by microbes is still missing (Trivedi et al. 2018). It indicates an indirect relationship between the microbial community and their metabolic functions concerning SCS (Comte et al. 2013) posing the main hurdle in microbial data analysis.

3.8 Conclusions and Future Prospectives

The SOC in terrestrial ecosystems is an important component to maintain soil fertility. The SOC storage has a close association with microbial activity in soil along with the ecological processes such as plant photosynthesis, decomposition, and soil respiration. Elevating temperatures and CO_2 are predicted to generate complex patterns of SOC capacity in soil by altering microbial activity through different land use and management strategies at physically heterogeneous landscapes. Different management practices are useful for restoring soils and sequestering a very significant portion of atmospheric C. It is an urgent need to develop specific strategies for SCS in agriculture through the interaction between farmers, scientist, policymakers and climate negotiators, etc.

Bioinformatic analysis and integration of available data for precise application in SCS are required. Data available from genome sequencing, microbial mining, and microbial populations associated with specific soil types, factors influencing microbial efficacy to store SOC, new aspects of biogeochemical cycles of elemental C need to be assessed by researchers in collaboration from different fields such as microbiology, ecology, geochemistry, molecular biology, and bioinformatics (Trivedi et al. 2018). Modeling of these data will give some important answers about how SCS cycle functions in the environment and how it transforms microbial populations in different LMPs thereby affecting the soil fertility. Additionally, development of model organisms involved in SCS needed with all the practical information including their chemical, molecular and physiological parameters. Recently, microalgae *Nannochloropsis* spp. and diatom *Thalassiosira pseudonana* are being developed as a model system to study C sequestration and potential applications of modern genetic tools such as CRISPR/Cas system (Wang et al. 2016; Hopes et al. 2016). There is a great scope to improve bio-sequestration by terrestrial plants using modern genetic engineering techniques, for example by enhancing light interception efficiency, Improving biomass quality, increasing conversion of solar energy to biomass, increasing C allocation to roots (Jansson et al. 2010) that can be sequestered by microbial community.

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References

Abbott LK, Murphy DV (2007) What is soil biological fertility? In: Abbott LK, Murphy DV (eds) Soil biological fertility – a key to sustainable land use in agriculture. Springer, Dordrecht, pp 1–15

Allmaras RR, Schomberg HH, Douglas CL et al (2000) Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands. J Soil Water Conserv 55:365–373

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration what do we really know? Agric Ecosyst Environ 118:1–5

Baldock JA, Skjemstad JO (1999) Organic soil C/soil organic matter. In: Prveril KI, Sparrow LA, Reuter DJ (eds) Soil analysis: an interpretation manual. CSIRO Publishing, Collingwood, pp 159–170

Banwart S, Black H, Cai Z et al (2014) Benefits of soil carbon: report on the outcomes of an international scientific committee on problems of the environment rapid assessment workshop. Carbon Manage 5:185–192

Batjes NH (2006) Soil carbon stocks of Jordan and projected changes upon improved management of croplands. Geoderma 132:361–371

Bhattacharyya T, Pal DK, Velayutham M et al (2000) Total carbon stock in Indian soils: issues, priorities and management. Land resource management for food and environmental security. Soil Conservation Society of India, New Delhi, pp 1–46

Bolin B, Sukmar R, Cias P et al (2000) Global perspective. In: Watson RT, Noble IR, Bolin B et al (eds) Land use, land-use change, and forestry, a special report of the IPCC. Cambridge University Press, Cambridge, pp 23–51

Canadell JG, Kirscbaum M, Kurz WA et al (2007) Factoring out natural and indirect human effects on terrestrial carbon sources and sinks. Environ Sci Pol 10:370–384

Chenu C, Angers DA, Barré P et al (2018) Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. Soil Tillage Res. https://doi.org/10.1016/j.still.2018.04.011

Christensen BT (1996) Carbon in primary and secondary organo-mineral complexes. In: Carter MR, Stewart BA (eds) Structure and organic matter storage in agricultural soils. CRC Press, Boca Raton, pp 97–165

Clemmensen KE, Bahr A, Ovaskainen O et al (2013) Roots and associated fungi drive long term carbon sequestration in boreal forest. Science 339:1615–1618
Comte J, Fauteux L, del Giorgio PA (2013) Links between metabolic plasticity and functional redundancy in freshwater bacterioplankton communities. Front Microbiol 4:112
Dalal RC, Chan KY (2001) Soil organic matter in rainfed cropping systems of the Australian cereal belt. Aust J Soil Res 39:343–355
Dijkstra FA, Carrillo Y, Pendall E et al (2013) Rhizosphere priming: a nutrient perspective. Front Microbiol 4:216
Dungait JAJ, Hopkins DW, Gregory AS et al (2012) Soil organic matter turnover is governed by accessibility not recalcitrance. Glob Chang Biol 18:1781–1796
Eshwarn H, Berg EVD, Reich P (1993) Organic carbon in soils of the world. Soil Sci Soc Am J 57:192–194
Falloon PD, Smith P (2000) Modelling refractory soil organic matter. Biol Fertil Soils 30:388–398
Fang Y, Nazaries L, Singh BK et al (2018) Microbial mechanisms of carbon priming effects revealed during the interaction of crop residue and nutrient inputs in contrasting soils. Glob Chang Biol 24:2775–2790
FAO and ITPS (2015) Status of the world's soil resources (SWSR). Main report. Food and agriculture organization of the United Nations and Intergovernmental Technical Panel on soils, Rome, Italy, pp 1–648. Available at: http://www.fao.org/3/a-i5199e.pdf. Accessed Aug 2018
Fierer N, Bradford MA, Jackson RB (2007) Toward an ecological classification of soil bacteria. Ecology 88:1354–1364
Fierer N, Lauber CL, Ramirez KS et al (2012) Comparative metagenomics, phylogenetic, and physiological analyses of soil microbial communities across nitrogen gradients. ISME J 6:1007–1017
Finn D, Kopittke PM, Dennis PG, Dalal RC (2017) Microbial energy and matter transformation in agricultural soils. Soil Biol Biochem 11:176–192
Follett RF, Stewart CE, Pruessner EG et al (2012) Effects of climate change on soil carbon and nitrogen storage in the US Great Plains. J Soil Water Conserv 67:331–342
Fontaine S, Barot S, Barré P et al (2007) Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature 450:277–280
Gill GP, Wilcox PL, Whittaker DJ, Winz RA, Bickerstaff P, Echt CE, Kent J, Humphreys MO, Elborough KM, Gardner RC (2006) A framework linkage map of perennial ryegrass based on SSR markers. Genome 49(4):354–364
Glover JD, Reganold JP, Bell LW et al (2010) Agriculture. Increased food and ecosystem security via perennial grains. Science 328:1638–1639
Gougoulias C, Clark JM, Shaw LJ (2014) The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. J Sci Food Agric 94(12):2362–2371
Govindarajulu M, Pfeffer PE, Jin H et al (2005) Nitrogen transfer in the arbuscular mycorrhizal symbiosis. Nature 435:819–823
Grandy AS, Neff JC (2008) Molecular C dynamics downstream: the biochemical decomposition sequence and its impact on soil organic matter structure and function. Sci Total Environ 404:297–307
Grandy AS, Wickings K (2010) Biological and biochemical pathways of litter decomposition and soil carbon stabilization. Geochim Cosmochim Acta 74:A351–A351
Guo ZL, Cai CF, Li ZX et al (2009) Crop residue effect on crop performance, soil N_2O and CO_2 emissions in alley cropping systems in subtropical China. Agrofor Syst 76:67–80
Hoeksema JD, Chaudhary VB, Gehring CA et al (2010) A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi. Ecol Lett 13:394–407
Hopes A, Nekrasov V, Kamoun S, Mock T (2016) Editing of the urease gene by CRISPR-Cas in the diatom *Thalassiosira pseudonana*. Plant Methods 24(12):49
Hudson BD (1994) Soil organic matter and available water capacity. J Soil Water Conserv 49:189–194

Jansson CS, Wullschleger D, Kalluri UC, Tuskan GA (2010) Phytosequestration: carbon biosequestration by plants and the prospects of genetic engineering. Bioscience 60:685–696
Kane D (2015) Carbon sequestration potential on agricultural lands: a review of current science and available practices association with: national sustainable agriculture coalition breakthrough strategies and solutions, LLC. Available at: http://sustainableagriculture.net/publications. Accessed Aug 2018
King GM (2011) Enhancing soil carbon storage for carbon remediation: potential contributions and constraints by microbes. Trends Microbiol 19:75–84
Krull E, Baldock J, Skjemstad J (2001) Soil texture effects on decomposition and soil carbon storage. In: MUF K, Mueller R (eds) Net ecosystem exchange: CRC workshop proceedings. CRC for Greenhouse Accounting, Canberra, pp 103–110
Kuzyakov Y, Blagodatskaya E (2015) Microbial hotspots and hot moments in soil: concept and review. Soil Biol Biochem 83:184–199
Kuzyakov Y, Friedel JK, Stahr K (2000) Review of mechanisms and quantification of priming effects. Soil Biol Biochem 32(11–12):1485–1498
Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 340:1623–1627
Lal R (2008) Carbon sequestration. Philos Trans R Soc B Bio Sci 363:815–830
Lal R (2016) Soil health and carbon management. Food Energy Secur 5:212–222
Lefevre C, Rekik F, Alcantara V, Wiese L (2017) Soil organic carbon: the hidden potential. Food and Agriculture Organization of the United Nations (FAO), Rome, p 77
Lehmann L, Abiven S, Kleber M et al (2015) Persistence of biochar in soil. In: JAJS, Lehmann (eds) Biochar for environmental management – science, Routledge, pp 235–283
Lennon JT, Aanderud ZT, Lehmkuhl BK, DRJr S (2012) Mapping the niche space of soil microorganisms using taxonomy and traits. Ecology 93:1867–1879
Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. Funct Ecol 8:315–323
Lorenz K, Lal R, Preston CM, Nierop KGJ (2007) Strengthening the soil organic C pool by increasing contributions from recalcitrant aliphatic bio(macro) molecules. Geoderma 142:1–10
Luo YQ, Zhao XY, Olof A et al (2014) Artificial root exudates and soil organic carbon mineralization in degraded sandy grassland in northern China. J Arid Land 6:423–431
Martiny JB, Martiny AC, Weihe C, Lu Y, Berlemont R, Brodie EL et al (2017) Microbial legacies alter decomposition in response to simulated global change. ISME J 11(2):490
Mondal A, Khare D, Kundu S, Mondal S et al (2017) Spatial soil organic carbon (SOC) prediction by regression kriging using remote sensing data, Egypt. J Remote Sens Space Sci 20:61–70
Mummey DL, Rillig MC, Six J (2006) Endogenic earthworms differentially influence bacterial communities associated with different soil aggregate size fractions. Soil Biol Biochem 38:1608–1614
Murphy CJ, Baggs EM, Morley N et al (2015) Rhizosphere priming can promote mobilisation of N-rich compounds from soil organic matter. Soil Biol Biochem 81:236–243
Nair PKR, Nair VD, Kumar BM, Haile SG (2009) Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. Environ Sci Pol 12:1099–1111
O'Rourke SM, Angers DA, Holden NM, McCartney AB (2015) Soil organic carbon across scales. Glob Chang Biol 21:3561–3574
Oades JM (1995) An overview of processes affecting the cycling of organic carbon in soils. In: Zepp GG, Sonntag C (eds) The role of non-living organic matter in the Earth's C cycle. Dahlem workshop reports. Wiley, New York, pp 293–303
Olson KR, Al-Kaisi MM, Lal R, Lowery B (2014) Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. Soil Sci Soc Am J 78:348–360
Ontl TA, Schulte LA (2012) Soil carbon storage. Nat Educ Knowl 3(10):35
Orgiazzi A, Panagos P, Yigini Y, Dunbar MB, Gardi C, Montanarella L et al (2016) A knowledge-based approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity. Sci Total Environ 545:11–20
Pal DK, Wani SP, Sahrawat KL (2015) Carbon sequestration in Indian soils: present status and the potential. Proc Nat Acad Sci India Sect B Biol Sci 85:337–358

Poulton PR, Pye E, Hargreaves PR, Jenkinson DS (2003) Accumulation of carbon and nitrogen by old arable land reverting to woodland. Glob Chang Biol 9:942–955
Prescott CE (2010) Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils? Biogeochemistry 101(1–3):133–149
Rillig MC (2004) Arbuscular mycorrhizae, glomalin, and soil aggregation. Can J Soil Sci 84:355–363
Scharlemann JP, Tanner EV, Hiederer R, Kapos V (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management 5:81–91
Schmidt M, Noack A (2000) Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. Glob Biogeochem Cycles 14:777–793
Schreiner KM, Blair NE, Levinson W, Egerton-Warburton LM (2014) Contribution of fungal macromolecules to soil carbon sequestration. In: Soil carbon. Springer, pp 155–161
Schulte RPO, Creamer R, Donnellan T et al (2014) Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environ Sci Pol 38:45–58
Shelake RM, Waghunde RR, Morita EH, Hayashi H (2018) Plant-microbe-metal interactions: basics, recent advances, and future trends. In: Egamberdieva D, Ahmad P (eds) Plant microbiome: stress response. Microorganisms for sustainability, vol 5. Springer, Singapore, pp 1–5
Sinasbaugh RL (2010) Phenol oxidase, peroxidise and organic matter dynamics of soil. Soil Biol Biochem 42:391–404
Singh BK, Bardgett RD, Smith P, Reay DS (2010) Microorganisms and climate change: terrestrial feedbacks and mitigation options. Nat Rev Microbiol 8:779–790
Six J, Frey SD, Thiet RK, Batten KM (2006) Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Sci Soc Am J 70:555–569
Skinner RH, Sanderson MA, Tracy BF, Dell CJ (2006) Above and belowground productivity and soil carbon dynamics of pasture mixtures. Agron J 98:320–326
Smith SE, Read DJ (2008) Mycorrhizal symbiosis, 3rd edn. Cambridge University Press, London
Strickland MS, Rousk J (2010) Considering fungal: bacterial dominance in soils–methods, controls, and ecosystem implications. Soil Biol Biochem 42:1385–1395
Tiemann LK, Grandy AS, Atkinson EE et al (2015) Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecol Lett 18(8):761–771
Toberman H, Freeman C, Evans C et al (2008) Summer drought decreases soil fungal diversity and associated phenol oxidase activity in upland Calluna heathland soil. FEMS Microbiol Ecol 66:426–436
Torn MS, Trumbore SE, Chadwick OA et al (1997) Mineral control of soil organic carbon storage and turnover. Nature 389:170–173
Trivedi P, Anderson IC, Singh BK (2013) Microbial modulators of soil carbon storage: integrating genomic and metabolic knowledge for global prediction. Trends Microbiol 21:641–651
Trivedi P, Rochester IJ, Trivedi C et al (2015) Soil aggregate size mediates the impacts of cropping regimes on soil carbon and microbial communities. Soil Biol Biochem 91:169–181
Trivedi P, Delgado-Baquerizo M, Trivedi C et al (2016) Microbial regulation of the soil carbon cycle: evidence from gene–enzyme relationships. ISME J 10(11):2593
Trivedi P, Singh BP, Singh BK (2018) Soil carbon: introduction, importance, status, threat, and mitigation. In: Singh BK (ed) Soil carbon storage: modulators, mechanisms and modeling. Academic, San Diego, pp 1–28
Waghunde RR, Shelake RM, Shinde MS, Hayashi H (2017) Endophyte microbes: a weapon for plant health management. In: Microorganisms for green revolution. Springer, Singapore, pp 303–3025
Wang Q, Lu Y, Xin Y, Wei L, Huang S, Xu J (2016) Genome editing of model oleaginous microalgae *Nannochloropsis* spp. by CRISPR/Cas9. Plant J 88(6):1071–1081
Weltzin JF, Loik ME, Schwinning S et al (2003) Assessing the response of terrestrial ecosystems to potential changes in precipitation. Bioscience 53:941–952
Woodward FI, Bardgett RD, Raven JA, Hetherington AM (2009) Biological approaches to global environment change mitigation and remediation. Curr Biol 19:R615–R623

Wu H, Guo Z, Gao Q, Peng C (2009) Distribution of soil inorganic carbon storage and its changes due to agricultural land use activity in China. Agric Ecosyst Environ 129:413–421

Xia J, Wan S (2012) The effects of warming-shifted plant phenology on ecosystem carbon exchange are regulated by precipitation in a semi-arid grassland. PLoS One 7:32088

Yuste JC, Baldocchi DD, Gershenson A et al (2007) Microbial soil respiration and its dependency on carbon inputs, soil temperature and moisture. Glob Chang Biol 13:2018–2035

Zibilske LM, Bradford JM (2006) Oxygen effects on carbon, polyphenols and nitrogen mineralisation potential in soil. Soil Sci Soc Am J 71:133–139

4 Strategies to Improve Agriculture Sustainability, Soil Fertility and Enhancement of Farmers Income for the Economic Development

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Abstract

India is an agricultural country, 70% people depend on agriculture, because the only major means of farmer's income is agriculture. Intensive agriculture practiced without observance to the scientific principles and ecological aspects has led to loss of soil health, and reduction of freshwater resources and agrobiodiversity. With progressive diversion of arable land for non-agricultural purposes, the challenge of feeding the growing population without, at the same time, annexing more forestland and depleting the rest of life is indeed daunting. Additional, even with food availability through production, millions of marginal farming and landless rural families have very low or no access to food due to lack of income-generating livelihoods. Approximately 200 million rural women, children and men in India fall in this category. Under these circumstances, the evergreen revolution such as pro-nature, pro-poor, pro-women and pro-employment/livelihood oriented ecoagriculture under varied terms are proposed for achieving productivity in perpetuity. Indian farmers are becoming poor due to the daily deterioration in agriculture, the main reasons for this, not receiving quality based seeds, delay water irrigation, reduced soil fertility and excessive use of chemical fertilizers. In order to remove these problems, we have been to develop a new strategy which will double the income of the farmers and make the soil fertile without the use of chemical fertilizers. Our government is constantly trying for it, which help

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farmers to get maximum benefit and improve our agriculture from launch new schemes for water, seed, nutrients and insurance the crops are started and organizing time to time a mega fair for providing basic knowledge for the farmers. So that more and more farmers are aware of it and use good machinery, seeds, and biofertilizers in their agriculture, so that their income accompanied, soil fertility can also be increased. Agricultural research are constantly probing fertile seeds, improve nutrition and organic fertilizers which will help us to grow agriculture. Fifty decades before came green revolution, which improved crops yield and productivity, while today need to be evergreen revolution for agricultural improvement, for doubling farmers income, enhance crop productivity and also improve soil fertility. The principles, strategies, models for sustainable agriculture and pathways for doubling farmers income are described in this book chapter.

Keywords

Crop yields · Evergreen revolution · Farmers income · Sustainable agriculture strategy

4.1 Introduction

Agriculture faces many challenges, making it more and more difficult to achieve its primary objective feeding the world each year. Population growth and changes in diet associate with rising incomes drive greater demand for food and other agricultural products, while global food systems are increasingly threatened by land degradation, climate change, and other stressors. Uncertainties exist about regional and local impacts of climate change, but the overall global pattern suggests that the stability of the food system will be at greater risk due to short term variability in food supply. Farmers are at the epicenter of Indian economy and their livelihood upliftment is a step towards holistic development of the nation. Decline in productivity and income has a serious implication on rural household poverty, and other economic, social as well as sustainability indicators (Timmer 1995; Datt and Ravallion 1998; Fan et al. 2000; Mellor 2000; Irz et al. 2001; Byerlee et al. 2005; Minten and Barrett 2008; Muyanga et al. 2013). Hence, increasing the income of farmers from different sources across holding size and region has become an utmost priority for the policy planners. Though, the state goes rhetoric about farmers' welfare since independence, its policies have always been consumer centric preventing the producers from relishing the fruits of their labor and hard work. The agriculture policies have led to a 'boom-bust' cycle in agriculture with a certain regularity that a year of drought leads to prices shoot up, area increase, abundant production collapse of prices, area shrinkage and prices shoot up. The Government, in its 2016–17 budget, with the intention of going beyond the food security objective, gave enough policy thrust on income security proposing to the double the farmers' income by 2022 indicated that it is not a mere rhetoric but a serious resolve (Sendhil et al. 2017a).

The green revolution of the 1960s and 1970s which resulted in dramatic yield increases in the developing. The Green Revolution today is the stuff of legend. The literature of the green revolution can never be monocultural. The diversity of perspectives from which it has been analyzed is impressive. The political scientist, Varshney (1998) has provided a political economy of the green revolution contrasting the Nehru Mahalanobis and Charan Singh models. The physicist Shiva (1991) from a feminist ecological perspective has produced a provocative link between green revolution and the terrorism and ethnic violence that followed in Punjab. If Varshney is replete with policy documents, Shiva's study unravels the green revolution from civic consciousness of an alternative agriculture. Anderson et al. 1991, a Canadian anthropologist studied the Rockefeller Foundation archive to read the green revolution as another great module of US foreign policy.

In making the transition from the green revolution to the biotechnology revolution one must emphasize that the line marking the two was not a border but a threshold. The movement to the second involved a political risk of passage through what anthropologist cold call a limenal space a period when categories, concepts, institutions had to be exercised and questioned. It was a period when the democratic imagination reworked itself beyond the standard categories of electorism development and state sovereignty. To move from green revolution to biotechnology is to create textbook history where dissent, doubt, eccentricity that haunted the years of debate on science and development is erased or lost. A linear or conventional history will not do. Such a narrative would begin once again with the invocation of the demographic trap where the green revolution gets defined as a mere breathing space, a transition, a problem solving technique that has been outrun by the pace of the problem. We must remember Thomas Kuhn's warning that the new paradigm often creates policy histories where the dissenting and the defeated and recessive have no spaces.

The question is does the current state of biotechnology allow transition to the evergreen revolution. The answer is that the current regimes lack the framework of concepts the consensual framework of innovative categories that the Green revolution had. One virtually needs to invent new forms of constitutionalism. The environmental policies advocated in the richer nations are designed to protect the high standard of living associated with the unprecedented growth in the exploitation of natural resources during the last century. It is of necessity a policy based on a series of don'ts. The poor nations in contrast are faced with the desire and the need to produce more food from hungry, thirst soils. They hence need a do ecology rather than a don't philosophy (Kesavan and Swaminathan 2008).

Sustainability becomes as it were a matrix, an amniotic cocoon within which he developed his later concepts. A wag once said that sustainability like the nation state is a refuge of the scoundrels and dissenting self-reflective scientists. Initially two concepts seem to compete in his scheme- sustainability and food security. If the earlier green revolution talked of scarcity, productivity and national security Swaminathan feels that the activist connotations of the word security must be transferred from the nation to food. Butler not guns needs more activist notions. But security is a network of concepts. Food security at the individual level needs security of livelihoods. Ecological security is the foundation on which food and livelihood security rest (Swaminathan 1999). Security and sustainability become a continuum in his work.

The scientist also realizes that physicalist notions of productivity will not do. One needs not just the availability of food, but economic access to it. Equally vital was the nutritional vitality of food. Malnourishment is also denial of access. It is around the philosophy of food that Swaminathan disaggregates the concepts of poverty to focus on women, children and marginals. Once poverty is disaggregated one moves from Malthusian scarcity to deprivation and eventually equity. The poor are poor only because they have no assets. Development now is asset building and value adding to the world of poor. Suddenly sustainability becomes a rainbow concept to include dimensions of economic viability, environmental soundness and social equity. Swaminathan political theory is a continuous search for new definitions and monitoring tools to reject this paradigm shift in the approach to development.

Modern agriculture now feeds 6000 million people. Global cereal production has doubled in the past 40 years. Mainly from the increased yields resulting from greater inputs of fertilizer, water (FAO 2003) and pesticides, new crop strains, and other technologies of the 'Green Revolution' (WHO 1990; Tilman et al. 2001; FAO 2003). This has increased the global per capita food supply (FAO 2003), reducing hunger, improving nutrition (and thus the ability of people to better reach their mental and physical potential) and sparing natural ecosystems from conversion to agriculture (Tilman et al. 2001). By 2050, global population is projected to be 50% larger than at present and global grain demand is projected to double (Alexandratos 1999; Cassman 1999; Cohen and Fedoroff 1999). This doubling will result from a projected 2.4-fold increase in per capita real income and from dietary shifts towards a higher proportion of meat (much of it rainfed) associated with higher income. Further increases in agricultural output are essential for global political and social stability and equity. Doubling food production again, and sustaining food production at this level, are major challenges (Alexandratos 1999; Postel 1999; Ruttan 1999, 2002). Doing so in ways that do not compromise environmental integrity (Vitousek et al. 1997b, Carpenter et al. 1998; Tilman et al. 2001) and public health (Smith et al. 1999; Gorbach 2001) is a greater challenge still. We focus here on scientific and policy challenges that must be met to sustain and increase the net societal benefits of intensive agricultural production.

Doubling farmers income 2022 is quite challenge but it is needed and is attainable. Three pronged strategy focused on (i) development initiatives (ii) technology and (iii) policy reforms in agriculture is needed to double farmer's income. The rates of increase in source underlaying growth in output need to be accelerated by 33% to meet the goal. The country need to increase use of quality seeds, fertilizers and power supply to agriculture by 12.8, 4.4 and 7.6% every year. Area under irrigation has to be expanded by 1.78 million hectare and area under double cropping should be increased by 1.85 million hectare every year (Chand 2017). Agricultural sector received continuous attention of the policy makers and stakeholders. For the first time in our history, Hon'ble Prime Minister of India exhorted to "Double the Farmers' (DFI) Income" by 2021–22 and helped in channelizing the efforts in the unified direction. DFI goal was also coupled with many new and well-thought out schemes Pradhan Mantri Fasal Bima Yojana, e-National Agricultural Market, Paramparagat Krishi Vikas Yojana and Pradhan Mantri Krishi Sichai Yojana.

The present study analyzed the current status of farmers' income across holding size and regions and attempted to decipher the scope and pathways through potential drivers. The spatial and temporal trends in farm household income from crop production have been analyzed for better understanding of the present scenario. Second, a framework integrating technology, extension, institutions and policies to double the income by 2022 has been developed. The study also highlighted the strategies to double the income, a major staple food crops.

4.2 Challenges for Sustainable Agriculture

The challenges in agriculture are many in the context of doubling income. To cite a few, competition for land, water and energy; increasing cropping intensity leading to irrational resource use; changing pest complex; degradation of natural resources like land and water; declining total factor productivity; and stagnating yield (Sharma et al. 2013) (Fig. 4.1). Indian agriculture not only faces the above routine challenges as it gets transformed but their intensity gets magnified in lieu of climate change. Agriculture not only affected by climate change but serve as a mitigator too. The production challenges are interdependent wielding the influence at different magnitudes across regions which finally gets reflected at macro level with negative impact. Hence, framing adaptation and mitigation strategies for climate change becomes utmost priority in Indian agriculture in the perspective of increasing the farm household income. The complexity in addressing the production challenges embraced by the negative impact of climate change as shown in Fig. 4.1 needs an in-depth understanding of the local situation for implementing relevant management strategies.

4.3 Natural Resources for Sustainable Agriculture

Indicators such as crop yield or partial factor productivities of land, water, fertilizer, and labor show a less encouraging global picture (CGIAR 2015). Declining freshwater resources, rising energy prices, or low efficiency of nitrogen fertilizer affect many former Green Revolution regions (Dobermann and Cassman 2005) Fig. 4.2. Recognizing that each country has different staple crops that form the basis for food and nutritional security, a major global concern is the slowing yield growth in cereal crops are the basis of food security in many parts of the world (Cassman et al. 2003; Fischer and Edmeades 2010). On the other hand, many improved agronomic practices can still lead to higher yields and/or higher efficiencies and greater sustainability in many farming systems. Rainfed farmers, for example, appear to have relatively large yield gaps (50% or more) that persist largely for agronomic, economic and social reasons (Lobell et al. 2009). There is also strong evidence for decreasing crop yield growth due to rising temperatures and uncertainty in growing

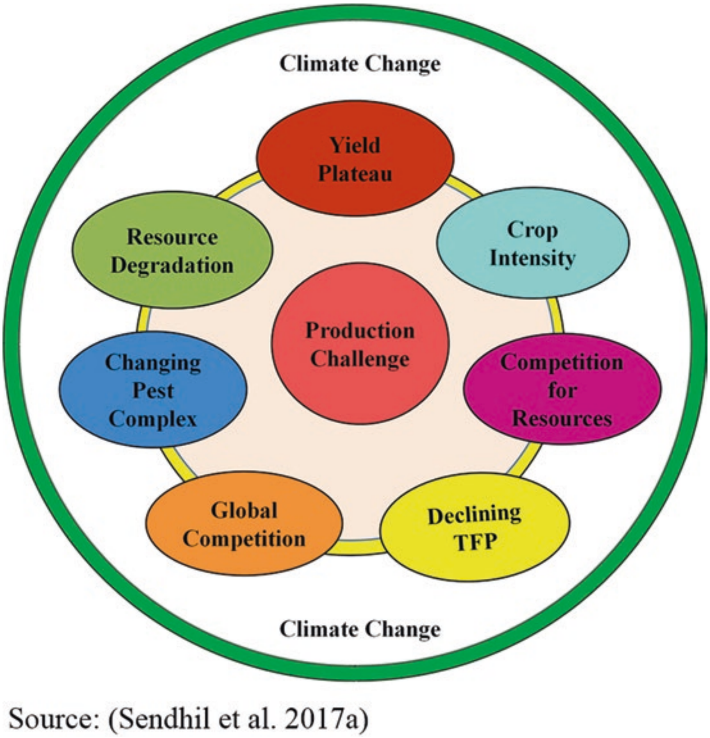

Fig. 4.1 Challenging reasons for sustainable agriculture system. (Source: Sendhil et al. 2017a)

season weather. More broadly, climate change will affect agriculture in many ways, requiring substantial investments in designing and implementing climate-smart food system.

4.4 Raising Water-Use Efficiency

Irrigation has ever been an important factor in agricultural development. The area of land under irrigation in the world has expanded substantially, particularly in the second half of the last century. Between the mid-1960s and the mid-1980s, expansion of irrigation has accounted for more than 50% increase in global food production (El-Ashry and Duda 1999). Although only approximately 17% of the world's cropland is irrigated, it produces more than a third of the food and fiber harvested throughout the world (Helalia et al. 1992). The expansion in irrigated agriculture needs to continue as the population increases, but annual renewable freshwater resources for the foreseeable future are now largely allocated. There may be some areas where freshwater resources increase or decrease according to rainfall changes due to climate change, however, these are likely to occur at the level that is small compared to the increased future demands for freshwater (Wallace 2000).

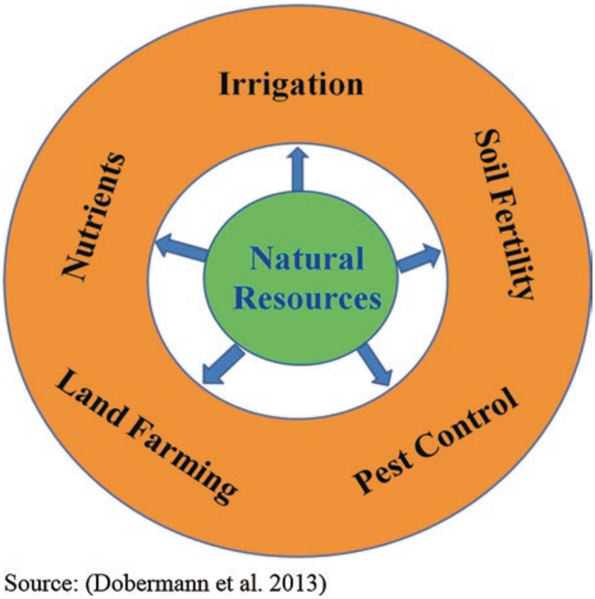

Fig. 4.2 Environmental effects responsible for sustainable agriculture. (Source: Dobermann et al. 2013)

Forty percent of crop production comes from the 16% of agricultural land that is irrigated (Gleick 1993; Postel et al. 1996). Irrigated lands account for a substantial portion of increased yields obtained during the Green Revolution. Unless water-use efficiency is increased, greater agricultural production will require increased irrigation. However, the global rate of increase in irrigated area is declining, per capita irrigated area has declined by 5% since 1978, and new dam construction may allow only a 10% increase in water for irrigation over the next 30 years (Dynesius and Nilsson 1994; Postel et al. 1996). Moreover, water is regionally scarce. Many countries in a band from China through India and Pakistan, and the Middle East to North Africa either currently or will soon fail to have adequate water to maintain per capita food production from irrigated land (Seckler et al. 1999). Roughly 20% of the irrigated area of the United States is supplied by groundwater pumped in excess of recharge, and over pumping is also a serious concern in China, India and Bangladesh (Sandra 1997).

Urban water use, restoration of streams for recreational, freshwater fisheries, and protection of natural ecosystems are all providing competition for water resources previously dedicated to agriculture. Finally, irrigation return-flows typically carry more salt, nutrients, minerals and pesticides into surface and ground waters than in source water, impacting downstream agricultural, natural systems and drinking water. Technologies such as drip and pivot irrigation can improve water-use efficiency and decrease salinization while maintaining or increasing yields. They have been used in industrialized nations on high-value horticultural crops, but their expanded use currently is not economically viable for staple food crops.

In developing countries, 15 million hectares have experienced reduced yields owing to salt accumulation and water logging (Sandra 1997). The water-holding capacity of soil can be increased by adding manure or reducing tillage and by other approaches that maintain or increase soil organic matter. Cultivation of crops with high water-use efficiency, and the development through the use of biotechnology or conventional breeding of crops with greater drought tolerance can also contribute to yield increases in water-limited production environments (Charles 2001; DeVries and Toenniessen 2001). Investment in such water-efficient technologies, however, is best facilitated when water is valued and priced appropriately. As supplies of good-quality irrigation water are expected to decrease, available water supplies need to be used more efficiently (Oweis 1999; Hatfield et al. 2001; Wichelns 2002), where one of the techniques can be the reuse of saline and or sodic drainage waters generated by irrigated agriculture (Shalhevet 1994; Rhoades 1999; Oster 2000), or of marginal-quality waters generated by municipalities (Bond 1998; Bouwer 2002). The same applies to salt-affected soils, which occupy more than 20% of the irrigated lands (Ghassemi et al. 1995), and warrant attention for efficient, inexpensive and environmentally acceptable reclamation and management to improve crop production (Qadir and Oster 2002).

4.5 Sustaining and Ameliorating Soil Fertility

Soil health is fundamental for agricultural sustainability, yet is under widespread threat from degradation processes Agricultural sustainability starts with the soil by seeking both to reduce soil erosion and to make improvements to soil physical structure, organic matter content, water-holding capacity and nutrient balances. Soil health is improved through the use of legumes, green manures and cover crops, incorporation of plants with the capacity to release phosphate from the soil into rotations, use of composts and animal manures, adoption of zero-tillage, and use of inorganic fertilizers where needed (Kibblewhite et al. 2008). Farmers are now adapting technologies organic matter levels have sufficiently improved that fertilizer use has been reduced and rainfall infiltration improved, such that some farmers are removing contour terraces. A public good is also being created when soil health is improved with increased organic matter. Soil organic matter contains carbon, and soils with above-ground biomass can act as ‘carbon sinks’ or sites for carbon sequestration Conservation tillage systems and those using legumes and/or cover crops contribute to organic matter and carbon accumulation in the soil (Pretty et al. 2003).

Fertile soils with good physical properties to support root growth are essential for sustainable agriculture, but, since 1945, approximately 17% of vegetated land has undergone human-induced soil degradation and loss of productivity, often from poor fertilizer and water management, soil erosion and shortened fallow periods (Oldeman 1992). Continuous cropping and inadequate replacement of nutrients removed in harvested materials or lost through erosion, leaching or gaseous emissions deplete fertility and cause soil organic matter levels to decline, often to half or less of original levels (Matson et al. 1998). Soil tillage speeds decomposition of soil organic matter and the release of mineral nutrients. Erosion can be severe on steep slopes where windbreaks have been cleared, vegetative cover is absent during the rainy season, and where heavy machinery is involved in land preparation (Naylor 1996). The effects of land degradation on productivity can sometimes be compensated for by increased fertilization, irrigation, and disease control, which increase production costs (Naylor 1996). Crop rotation, reduced tillage, cover crops, fallow periods, manuring and balanced fertilizer application can help maintain and restore soil fertility.

4.5.1 Ameliorate Nutrients

Intensive high-yield agriculture is dependent on addition of fertilizers, especially industrially produced NH_4 and NO_3. In some regions of the world, crop production is still constrained by too little application of fertilizers (Pinstrup-Andersen and Pandya-Lorch 1996). Without the use of synthetic fertilizers, world food production could not have increased at the rate it did and more natural ecosystems would have been converted to agriculture. Between 1960 and 1995, global use of nitrogen fertilizer increased sevenfold, and phosphorus use increased 3.5-fold both are expected to increase another threefold by 2050 unless there is a substantial increase in fertilizer efficiency (Cassman and Pingali 1995; Tilman et al. 2001). Fertilizer use and legume crops have almost doubled total annual nitrogen inputs to global terrestrial ecosystems (Vitousek and Matson 1993; Galloway et al. 1994). Similarly, phosphorus fertilizers have contributed to a doubling of annual terrestrial phosphorus mobilization globally (Carpenter et al. 1998). Further increases in nitrogen and phosphorus application are unlikely to be as effective at increasing yields because of diminishing returns. All else being equal, the highest efficiency of nitrogen fertilizer is achieved with the first increments of added nitrogen; efficiency declines at higher levels of addition.

Today, only 30–50% of applied nitrogen fertilizer (Smil 1999; Cassman et al. 2002) and ~45% of phosphorus fertilizer is taken up by crops. A significant amount of the applied nitrogen and a smaller portion of the applied phosphorus is lost from agricultural fields. This nitrogen contributes to reverie input into the North Atlantic that is 2- to 20-fold larger than in preindustrial times (Howarth et al. 1996). Such non-point nutrient losses harm off-site ecosystems, water quality and aquatic ecosystems, and contribute to changes in atmospheric composition (Vitousek et al. 1997b, Carpenter et al. 1998; Matson et al. 1998; Tilman et al. 2001). Nitrogen loading to estuaries and coastal waters and phosphorus loading to lakes, rivers and streams are responsible for over-enrichment, eutrophication and low-oxygen conditions that endanger fisheries (Council 1999a, Downing et al. 1999). Nitrogen fertilization can increase emission of gases that have critical roles in tropospheric and stratospheric chemistry and air pollution (Cicerone and Oremland 1988; Hall et al. 1996). Nitrogen oxides (NOx), emitted from agricultural soils and through combustion, increase tropospheric ozone, a component of smog that impacts human health, agricultural crops and natural ecosystems. As much as 35% of cereal crops worldwide are exposed to damaging levels of ozone. NOx from agroecosystems can be transported atmospherically over long distances and deposited in terrestrial and aquatic ecosystems. This inadvertent fertilization can cause eutrophication, loss of diversity, dominance by weedy species and increased nitrate leaching or NOx fluxes (Vitousek et al. 1997a). Finally, nitrogen inputs to agricultural systems contribute to emissions of the greenhouse gas nitrous oxide. Rice paddy agriculture and livestock production are the most important anthropogenic sources of the greenhouse gas methane (Vitousek et al. 1997a).

Solutions to these problems will require significant increases in nutrient-use efficiency, that is, in cereal production per unit of added nitrogen, phosphorus and water. There are a variety of practices and improvements that could each contribute to increased efficiency. The development and preferential planting of crops and crop strains that have higher nutrient-use efficiency are clearly essential. Cover crops or reduced tillage can reduce leaching, volatilization and erosional losses of nutrients and increase nutrient use efficiency. Closing the nitrogen and phosphorus cycles, such as by appropriately applying livestock and human wastes, increases cereal production per unit of synthetic fertilizer applied. Reliance on organic nutrient sources is a central feature of organic agriculture, but it is unclear whether the 'slow release' of nutrients from organic compost or green manures can be adequately controlled to match crop demand with nutrient supply to increase nitrogen-use efficiency in intensive cereal production systems, thereby decreasing losses to leaching and volatilization. More research on improving efficiency and minimizing loses from both inorganic and organic nutrient sources is needed to determine costs, benefits and optimal practices.

Nutrient-use efficiency is increased by better matching temporal and spatial nutrient supply with plant demand. Applying fertilizers during periods of greatest crop demand, at or near the plant roots, and in smaller and more frequent applications all have the potential to reduce losses while maintaining or improving yields and quality (Matson et al. 1996; Peng et al. 1996; Matson et al. 1998). Such 'precision agriculture' has typically been used in large-scale intensive farming, but is possible at any scale and under any conditions given the use of appropriate diagnostic tools 6 Strategies that synchronize nutrient release from organic sources with plant demand are also needed (Myers et al. 1994; Robertson 1997). Multiple cropping systems using crop rotations or intercropping (two or more crops grown simultaneously) may improve pest control and increase nutrient- and water-use efficiency.

Agroforestry, in which trees are included in a cropping system, may improve nutrient availability and efficiency of use and may reduce erosion, provide firewood and store carbon. Landscape-scale management holds significant potential for reducing off-site consequences of agriculture. Individual farms, watersheds and regional planning can take advantage of services provided by adjacent natural, semi-natural or restored ecosystems. Trees and shrubs planted in buffer strips surrounding cultivated fields decrease soil erosion and can take up nutrients that otherwise would enter surface or ground waters. Buffer zones along streams, rivers and lakeshores can decrease nutrient and silt loading from cultivated fields or pastures. Crop pollination can be provided by insects and other animals living in nearby habitats or buffer strips, whereas other organisms from these habitats, such as parasitoids, can provide effective control of many agricultural pests. Buffer strips can also be managed to reduce inputs of weeds and other agricultural pests. The procurement of such ecosystem services will require landscape-level management.

4.6 Modern Land Farming

One persistent question regarding the potential benefits of more sustainable agroecosystems centres on productivity trade-offs. If environmental goods and services are to be protected or improved, what then happens to productivity? If it falls, then more land will be required to produce the same amount of food, thus resulting in further losses of natural capital (Green et al. 2005). As indicated earlier, the challenge is to seek sustainable intensification of all resources in order to improve food production. In industrialized farming systems, this has proven impossible to do with organic production systems, as food productivity is lower for both crop and livestock systems (Lamkin 1994; Caporali et al. 2003). Nonetheless, there are now some 3 Mha of agricultural land in Europe managed with certified organic practices. Some have led to lower energy use (though lower yields too), others to better nutrient retention and some greater nutrient losses (Goodman et al. 1997; Dalgaard et al. 1998; Løes and Øgaard 2003), and some to greater labor absorption (Pretty 2005; Morison et al. 2008).

Many other farmers have adopted integrated farming practices, which represent a step or several steps towards sustainability. What has become increasingly clear is that many modern farming systems are wasteful, as integrated farmers have found they can cut down many purchased inputs without losing out on profitability (Bragg 2005). Some of these cuts in use are substantial, others are relatively small. By adopting better targeting and precision methods, there is less wastage and more benefit to the environment. They can then make greater cuts in input use once they substitute some regenerative technologies for external inputs, such as legumes for inorganic fertilizers or predators for pesticides. Finally, they can replace some or all external inputs entirely over time once they have learned their way into a new type of farming characterized by new goals and technologies (Pretty and Ward 2001).

4.7 Prevention Against Disease and Pest

Chemical-based strategies have been the preferred form of pest control in agriculture since the 1950s and have contributed to an unprecedented growth in agricultural production and productivity (Pimentel et al. 1978, 1992, 1993). Since the end of the 1970s, the on-farm benefits of pesticide use has been weighed against concerns over the off-farm costs of pesticide risks to human health and the environment. The wider perspective prompted many regulatory agencies, at both national and international levels, to implement different types of pesticide risk management policies. These policies ranged from liability rules to market-based instruments and from command and control approaches to incentives for voluntary action including moral persuasion. Still, management of pesticide risks is a difficult task for policy makers (Travisi et al. 2006; Ahmed 2008).

Pests are the main constraints of a successful crop production. Worldwide crop losses due to agricultural pests are estimated to be about 15–25% and potential losses 30–40% (Mintz and Du Bois 2002; Aziz 2005). The crop loss varies due to the particular crop, place, time and farmers' knowledge. To address the pest problems a variety of methods can be used e.g. resistant variety, cultural and physical control, biological control, botanical control as well as chemical control. The principle of integrated pest management (IPM) is to primarily utilize other control methods and only as the last choice the chemical method. Crop researchers often advice farmers to use pesticides when pests are reaching the economic threshold level (ETL). However, sometimes these advices are not followed but instead pesticides are used indiscriminately and at substandard or higher doses. The latter might be especially common in developing countries with a lower degree of education among farmers. The indiscriminate use of pesticides may result in pest resurgence, and polluted soil, air and water. Though pesticides control pests, they also commonly kill natural enemies of pests. Main user of pesticides in developing countries is farmers within rural societies (FAO 2005). In urban and periurban societies including farms and agriculture, the proper use of pesticides is of utmost importance due to the often relatively densely populated surroundings (Ferrier et al. 2006).

Improvements in the control of weedy competitors of crops, crop diseases and pathogens, and herbivores could significantly increase yields. Three cereals wheat, rice and corn provide 60% of human food. These crops, derived from once-rare weedy species, have become the three most abundant plants on Earth. A central conclusion of epidemiology is that both the number of diseases and the disease incidence should increase proportional to host abundance, and this disconcerting possibility illustrates the potential instability of a global strategy of food production in which just three crops account for so high a proportion of production. The relative scarcity of outbreaks of diseases on these crops is a testament to plant breeding and cultivation practices. For all three cereals, breeders have been successful at improving resistances to abiotic stresses, pathogens and diseases, and at deploying these defenses in space and time so as to maintain yield stability despite low crop diversity in continuous cereal systems. However, it is unclear if such conventional breeding approaches can work indefinitely. Both integrated pest management and biotechnology that identifies durable resistance through multiple gene sources should play increasingly important roles (Ortiz 1998; DeVries and Toenniessen 2001) Nonetheless, the evolutionary interactions among crops and their pathogens mean that any improvement in crop resistance to a pathogen is likely to be transitory. Each defense sows the evolutionary seeds of its own demise (Palumbi 2001).

4.8 Sustainable Agriculture

Many different expressions have come to be used to imply greater sustainability in some agricultural systems over prevailing ones (both preindustrial and industrialized). These include biodynamic, community based, ecoagriculture, ecological, environmentally sensitive, extensive, farm fresh, free range, low input, organic, permaculture, sustainable and wise use (Pretty 1995, 2005; Cox et al. 2004; Scherr and McNeely 2008; Conway and Pretty 2013). There is continuing and intense debate about whether agricultural systems using some of these terms can qualify as sustainable (Balfour 1943; Lamkin 1994; Trewavas 2002; Altieri 2018). Systems high in sustainability can be taken as those that aim to make the best use of environmental goods and services while not damaging these assets (Pretty 1995, 2005; Altieri and Faminow 1996; Conway 1998; Council 1999b, Hinchcliffe et al. 1999; Li 2001; Pretty and Ward 2001; Tilman et al. 2002; Uphoff 2002; McNeely and Scherr 2003; Gliessman 2004; Swift et al. 2004; Tomich et al. 2004; Gliessman 2005; Meyer-Aurich 2005; Pretty and Hine 2005; Pretty and Waibel 2005; Kesavan and Swaminathan 2008; Scherr and McNeely 2008).

The key principles for sustainability are to: (i) integrate biological and ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration, allelopathy, competition, predation and parasitism into food production processes, (ii) minimize the use of those non-renewable inputs that cause harm to the environment or to the health of farmers and consumers, (iii) make productive use of the knowledge and skills of farmers, thus improving their self-reliance and substituting human capital for costly external inputs, and (iv) make productive use of people's collective capacities to work together to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management.

Agricultural sustainability suggests a focus on both genotype improvements through the full range of modern biological approaches and improved understanding of the benefits of ecological and agronomic management, manipulation and redesign. The ecological management of agroecosystems that addresses energy flows, nutrient cycling, population-regulating mechanisms and system resilience can lead to the redesign of agriculture at a landscape scale. Sustainable agriculture outcomes can be positive for food productivity, reduced pesticide use and carbon balances. The interest in the sustainability of agricultural and food systems can be traced to environmental concerns that began to appear in the 1950s–1960s. However, ideas about sustainability date back at least to the oldest surviving writings from China, Greece and Rome (Hesiod and Morrissey, 1983; Conway 1998; Li 2001; Pretty and Ward 2001; Pretty and Waibel 2005). Today, concerns about sustainability centre on the need to develop agricultural technologies and practices that: (i) do not have adverse effects on the environment (partly because the environment is an important asset for farming), (ii) are accessible to and effective for farmers, and (iii) lead to both improvements in food productivity and have positive side effects on environmental goods and services. Sustainability in agricultural systems incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods), and addresses many wider economic, social and environmental outcomes.

4.9 Economical Agriculture Sustainability

In recent years there has occurred a major revision in development thinking that is presenting a fundamental challenge to the conventional consensus on economic development. This new approach emphasizes meeting the basic needs of the poor, advocate cultural sensitivity, and encourages 'grassroots' participation in the development process. More crucially, it stresses that 'real' improvement cannot occur in Third World countries or anywhere else unless the strategies which are being formulated and implemented are environmentally sustainable. As a result, there is a growing 'recognition that the overall goals of environment and development are not in conflict but are indeed the same, namely the improvement of the human quality of life or welfare for present and future generations' (Bartelmus 1986).

Ethically in agriculture evolution, ecosystems are transformed into hybrid agroecosystems for the purpose of food or fiber production (Conway 1985). While agricultural sustainability requires the organic material of the soil to be replenished, this criterion can be met in a number of ways by both subsistence and surplus agricultural systems example, there exist many 'naturally subsidized solar-powered ecosystems', such as tidal estuaries and river deltas, where biomass productivity is greatly enhanced by the flowing of water that assists the importation of organic matter and nutrients from other regions (Odum 1997). Many important agroecosystems (e.g. delta-based agricultural systems) have traditionally tapped these regions to produce a surplus without much loss of sustainability—precisely because the natural flow of organic material into the system continues to maintain the latter's fertility. In fact, many agro-ecosystems are not closed' with respect to material cycling but are interdependent on one another and on other natural ecosystems for a continuous inflow of organic material and nutrients to maintain soil quality (e.g. natural soil and nutrient runoff from the highland, fertilizing lowland agricultural areas). In these instances '100% recycling of organic materials' is not necessary to avoid long-term soil degradation; instead, what is required are agricultural techniques and practices that do not degrade soil quality and ecological functions at a rate faster than the natural cycles and flows can 'repair' the damage.

Moreover, in many instances of sustainable rural or agricultural 'development', one is talking about transforming a system that was previously unsustainable into one that is at least relatively sustainable. A good example is a World Neighbors project in Honduras (Bunch 1988). At a cost of $ 13 per person, the Guinope Integrated Development Program has transformed a previously unsustainable smallholder agro-ecosystem through appropriate agricultural technology, training, and erosion control including intercropping of 'green manure' crops with the traditional corn or sorghum into a surplus-producing system with yield increases of over 300%

and a marketable surplus of vegetables. Even in drought-prone Africa, there are numerous successes in improving agricultural sustainability ranging from the large-scale Kenyan Soil and Water Conservation Programme to the Yatenga Water Harvesting Project in Burkina Faso (Harrison 1987). Finally, if maintaining the nutrient levels and organic material of soil is a necessary condition for agricultural sustainability, there should be no fundamental problems in maintaining an agro-ecosystem by 'some increase of external inputs' provided those inputs are ecologically benign or even beneficial (e.g. organic fertilizers, appropriate biotechnology, integrated pest management, etc.). If the acquisition of those additional inputs actually improves soil quality sufficiently to raise productivity, then farmers may be better off with them than they were formerly. For example, a Lutheran World Relief project in Niger will have built an estimated 3200 wells by the end of 1987. At an estimated cost of US $400 each, these wells have not only increased subsistence food output from project gardens but have also yielded a marketable surplus of between US $400 and 2000 per hectare. This has allowed gardeners to pay back the costs of the wells—to purchase seed, fertilizer, and other inputs, and to acquire valuable marketing skills (Cottingham 2013).

4.10 Globalization on Population Growth and Food Security

Global demand for agricultural crops is increasing, and may continue to do so for decades, propelled by a 2.3 billion person increase in global population and greater per capita incomes anticipated through midcentury (Godfray et al. 2010). Both land clearing and more intensive use of existing croplands could contribute to the increased crop production needed to meet such demand, but the environmental impacts and tradeoffs of these alternative paths of agricultural expansion are unclear (Godfray et al. 2010; Foresight 2011). Agriculture already has major global environmental impacts: land clearing and habitat fragmentation threaten biodiversity (Dirzo and Raven 2003), about one-quarter of global greenhouse gas (GHG) emissions result from land clearing, crop production, and fertilization (Burney et al. 2010), and fertilizer can harm marine, freshwater, and terrestrial ecosystems (Vitousek et al. 1997a). Understanding the future environmental impacts of global crop production and how to achieve greater yields with lower impacts requires quantitative assessments of future crop demand and how different production practices affect yields and environmental variables. Here, we forecast 2050 global crop demand and then quantitatively evaluate the global impacts on land clearing, nitrogen fertilizer use, and GHG release of alternative approaches by which this global crop demand might be achieved.

Global food demand is growing rapidly, much of the world's current cropland has yields well below their potential, and the current global trajectory of agricultural expansion has serious long-term implications for the environment. The environmental impacts of escalating crop demand will depend on the trajectory along which global agriculture develops. The preservation of global biodiversity and the minimization of the GHG impacts of agriculture may well hinge on this trajectory. A trajectory that adapts and transfers technologies to under yielding nations, enhances their soil fertility, employs more efficient nutrient use worldwide, and minimizes land clearing provides a promising path to more environmentally sustainable agricultural intensification and more equitable global food supplies.

4.11 Transforming the Green Revolution into an Evergreen Revolution

The term ‘Green Revolution’, coined by Dr. William Gaud of the US Department of Agriculture in 1968, has come to be associated not only with higher production through enhanced productivity, but also with several negative ecological and social consequences. There is also frequent reference to the ‘fatigue of the Green Revolution’, due to stagnation in Yield levels and to a larger quantity of nutrients required for producing the same yield as in the early 1970s. Experts have been warning about an impending global food crisis due to increasing population, increasing purchasing power leading to the consumption of more animal products, increasing damage to the ecological foundations of agriculture, declining per capita availability of land and water, and the absence of technologies that can further help to enhance the yield.

New strategy supported by appropriate services and public policies have helped prove doomsday predictions wrong and have led to the agricultural revolution (the Green Revolution) becoming one of the most significant of the scientific meaningful revolutions of this century. Four thousand years of wheat cultivation led to Indian farmers producing 6 million metric tons of wheat in 1947. The Green Revolution in wheat helped surpass in 4 years the production accomplishments of the preceding 4000 years, thus illustrating the power of technological changes’. There are uncommon opportunities now to harness the power of a new social contract among science, society and public policy to address contemporary development issues like the growing rich poor divide, feminization of poverty, famine of jobs, human numbers exceeding the population supporting capacity of ecosystems, climate change and loss of forests and biodiversity.

Fortunately, modern information technology provides opportunities for reaching the ‘unreached’. Computer aided and Internet-connected ‘Virtual Colleges’ linking scientists and women and men living in poverty can be established at local, national and global levels for launching a knowledge and skill revolution. This will help create better awareness of the benefits and risks associated with Genetically Modified Foods, so that both farmers and consumers will get better insights into the processes leading to the creation of novel genetic combinations (Swaminathan 2000).

4.12 Livelihood and Food Security in India

Rural people's livelihoods rely for their success on the value of services flowing from the total stock of natural, social, human, physical and financial capital (Coleman 1991; Putnam et al. 1994; Costanza et al. 1997; Carney 1998; Scoones 1998; Pretty and Ward 2001). A number of examples can be extracted from the dataset to show that agricultural sustainability projects and initiatives have been able to contribute to the accumulation of locally valuable assets. A selection of the impacts reported in these sustainable agriculture projects and initiatives include: (i) Improvements to natural capital, including increased water retention in soils, improvements in water table (with more drinking water in the dry season), reduced soil erosion combined with improved organic matter in soils, leading to better carbon sequestration, and increased agro-biodiversity (Hinchcliffe et al. 1996; Birdsey et al. 2000; McNeely and Scherr 2001, 2003; Pretty and Ball 2001). (ii) Improvements to social capital, including more and stronger social organizations at local level, new rules and norms for managing collective natural resources, and better connected to external policy institutions (Uphoff 2000; Pretty and Ward 2001). (iii) Improvements to human capital, including more local capacity to experiment and solve own problems; reduced incidence of malaria in rice—fish zones, increased self-esteem in formerly marginalized groups, increased status of women, better child health and nutrition, especially in dry seasons, and reversed migration and more local employment (KangMin 1992; Bunch 1999; Shah and Shah 1999; Rengasamy et al. 2000; Pretty and Uphoff 2001).

In practice, workable options actionable "solutions" must focus on raising the diversity, productivity, efficiency, resilience, value and therefore also the overall profitability of farming. This is the entry point for moving from the vicious circles trapping rural people in poverty or creating environmental problems towards virtuous circles of agriculture for sustainable development, It requires flexibility to adapt to new information and the recognition that the information upon which one takes initial action may, in retrospect, be misinformation. Sustainability will necessarily require trial and error, i.e., adaptive approaches on a grand scale one of the chief hurdles will be to deal with resistance to change. Raising productivity has additional benefits to those listed above; it is also an entry point for creating jobs and entering new domestic and export markets. If done properly, productivity-enhancing technologies reduce the unit cost of food production as well as the ecological footprint per unit of food produced. They lead to a supply shift and thus reduced equilibrium market prices for commodities. The reduced lower prices positively affect food and nutritional security and reduce poverty. But lowered prices also reduce the profitability of expanding cultivation into marginal areas, thus reducing the demand and the incentives for an agricultural incursion into remaining natural ecosystems. This, in turn, results in positive consequences, such as better conservation of biodiversity or fewer emissions of carbon stored in aboveground vegetative biomass or soils of the natural ecosystem virtuous circle can be greatly accelerated through efficient support systems: e.g., policies, infrastructure, markets research and development, human resources, digital information, and other tools.

4.13 The Challenges in Doubling Indian Farmer Incomes

The Niti Aayog recently came out with its 'Three Year Action Agenda' a plan that covers a time period that is politically crucial as it leads up to the 2019 Lok Sabha elections. In its chapter on agriculture titled '*Agriculture: Doubling Farmer's Incomes'*, the economic think-tank has put forth a four-point action plan to double the incomes of India's farmers. Although there is nothing radically new in what has been suggested by the Niti Aayog, the measures proposed are in the right direction if the farmers' incomes have to be doubled. However, various experts have cast a pall of gloom over the claim that is indeed possible to double incomes by 2022–23. This is primarily because agricultural growth in the post-reform period, barring a few exceptional years, has been stagnant and has historically failed to meet the target set by the government.

For example the average annual rate of growth in agriculture and allied sector during the period from 1991–92 to 2013–14 comes at 3.2%—lower than the targeted 4%. The four point action plan includes the following measures: (1) Remunerative prices for farmers by reforming the existing marketing structure; (2) Raising productivity; (3) Reforming agriculture land policy; and (4) Relief measures. It is important to see how these actions will double the income of the farmers' and to what extent the government is serious about it. It must be noted that agriculture and allied activities remains the main livelihood for more than half of the Indian population. The Socio-Economic and Caste Census (SECC) 2011, released in 2015, also indicates that out of 24.39 crore households in the country, 17.91 crore lived in villages and are more or less dependent on agriculture. Further, the Economic Survey of 2015–16 highlights that the share of agriculture in employment was 48.9% of the workforce while its share in gross domestic product (GDP) was 17.4% in 2014–15 at constant (2011–12) prices.

4.14 Strategies for Doubling Farmers Income

The strategy most frequently linked to sustainability is reduction or elimination of the use of processed chemicals, particularly fertilizers and pesticides (Madden 1987; Stinner and House 1987; Lockeretz 1988; Dobbs et al. 1990; Hauptli et al. 1990). In 1988, the US Department of Agriculture linked sustainability to levels of inputs by establishing the LISA research program (O'Connell 1990; Dicks 1992). Arguments for reducing chemical inputs include limited supplies of fossil fuels, decreasing commodity prices necessitating reducing input costs, a need for self-sufficiency, concerns about pollution, and health and safety concerns (Francis and

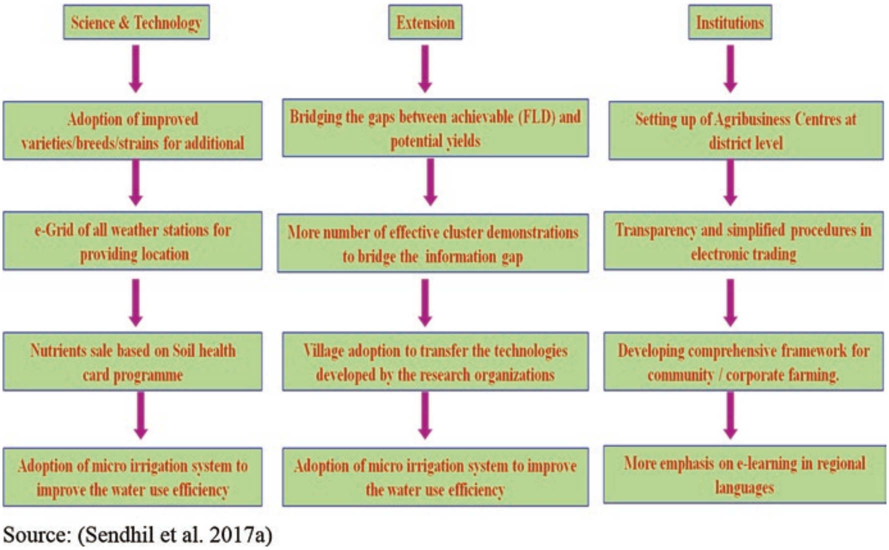

Fig. 4.3 Potential strategies to enhance farmers' income. (Source: Sendhil et al. 2017a)

King 1988; Carter 1989; Stinner and House 1989; MacRae et al. 1990; Rodale and Wagner 1990). York (1991) argued that fewer options exist for reducing fertilizer inputs than pesticide inputs in agricultural systems while maintaining sustainable production. Unlike pesticides, soil nutrient elements generally have no substitutes and are subjected to harvest and other losses that must be replaced by weathering or imported from outside the system if production is to be sustained. The high energy cost unique to N fertilizer production and the potential for biological fixation suggest a need and potential for seeking alternatives to synthetic N fertilizers that does not exist for mineral-based nutrients such as P and K. The important distinction between production systems that currently employ high levels of chemical inputs and those that employ low levels (Weil 1990) is often overlooked. Zandstra (1994) described sustainability as a function of chemical input levels. Excessive input levels were said to degrade natural resources through accumulation while inadequate levels degrade resources through exhaustion. This concept is in sharp contrast to the decreasing relationship between chemical input levels and sustainability proposed by Stinner and House (1987).

Income is the most relevant measure to assess the farmers' welfare and agriculture transformation. Even today, the highest returns on investment on per unit basis are from agriculture. What is lacking is the scale unlike corporate investment. Certainly, returns from cultivation alone will not help to achieve the set target of doubling farmer's income (DFI). It has to be supplemented, in fact to a larger extent by livestock and other non-farm activities supported with policy intervention at all levels (Chand 2017). Moreover, higher yields also correspond with improved seeds use. Hence, expanding irrigation and delivering improved seeds together could help in addressing yield gap successfully (Fig. 4.3).

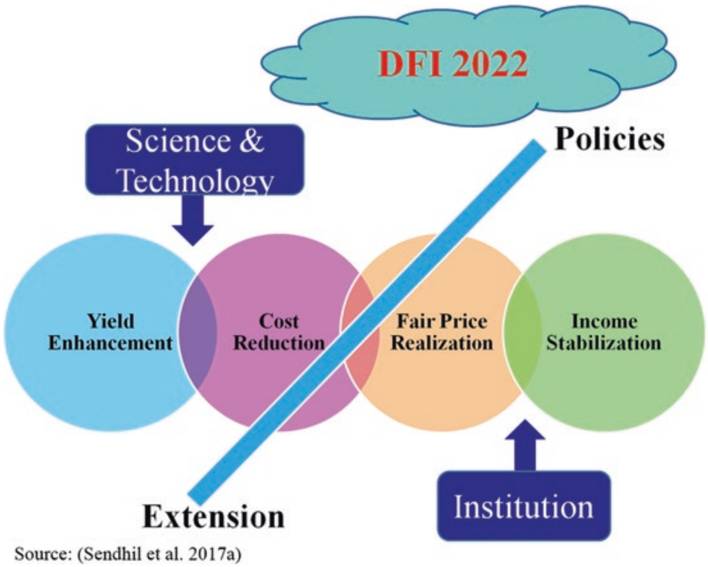

Fig. 4.4 Pathways for doubling farmers' income till 2022. (Source: Sendhil et al. 2017a)

4.14.1 Pathways for Doubling the Farmers Income

The scope for double farming income (DFI) by 2022 exists with the following options viz., increasing the physical output from agriculture, diversification of enterprises, pricing mechanism, adoption of risk management tools, wage rate and salaries for farm labour as well as different sources of non-farm income (Aayog 2015; Chand 2017; Raka et al. 2017). A pathway has been formulated which is applicable to all commodities and sectors in agriculture (Sendhil et al. 2017a, b). However, the implementation strategies should be region and need specific targeting different components in agriculture. The framework integrating technology, extension, institutions and policies to double the farmers' income has been depicted in Fig. 4.4.

Science and technology is the outcome of science enables increased output with the same input or realize the same output with reduced input. Productivity in a majority of the commodities has struck a plateau demanding barrier breaking intervention through cutting-edge sciences. The diversification of farm activities towards high value crops and enterprises can more than quadruple income from the same piece of land. Another augmenting factor for doubling farm income is through integrating crop production with allied and subsidiary enterprises in uncultivated lands.

Extension given the technology and resources, the output level can be enhanced by consolidating the existing potentials by bridging the yield gaps between agronomic potentials achieved in research and extension farms and the actual yields obtained in average farmer's fields. Around 30% of the physical output can be increased which will facilitate to increase the farmers' income without any additional investment, but just by adopting the recommended package of practices across different sub-sectors in agriculture.

In Institutions irrigation is the best insurance against drought. The thrust of the state is to ensure 'Per drop more crop' through accelerated irrigation schemes supplemented by massive promotion of micro irrigation techniques for maximum coverage of irrigated crop area. As agriculture in India is a gamble with the monsoon, and the economic pursuit of the enterprise is worth if and only when adequate risk management options are available. The recent initiatives of the government that is likely to impact agriculture can be broadly classified as those can prevent the volatility in farm income and those can improve the farm productivity. Any amount of productivity increase unless accompanied by farm income increase either by direct price incentive or cost reduction or economy of scale or value addition or anything else will have no meaning for farmers. The Pradhan Mantri Krishi Sinchai Yojana (PMKSY) promotes more crop per drop as a national mission to improve farm productivity with a focus on massive expansion of micro irrigation at farm level and by closely monitoring 99 priority projects with a potential of irrigating over 7.6 million ha for a faster completion. These will reduce the monsoon dependency insulating from shocks and improve productivity.

The recently initiated National Agricultural Marketing brings more than 500 markets on a single e-platform integrating markets sans middlemen and enabling farmers to bid their products to sell anywhere in India. But, the integration will have operational meaning for the farmers only when Agricultural Produce Market Committee (APMC) Act and Essential Commodities Act (ECA) are either revamped or done away with. This is very much evident in the difference in realization of the price potential between livestock products not covered under these acts and the fruits and vegetables covered under the APMC.

Policy on agricultural commodities export and stocking have more often than not acted against the farmers' interest preventing them from par taking the benefits of free market. Whenever prices shoot up, banning or restricting export or limiting stocking of the commodity have been resorted to more as a panic reaction than a planned strategic measure. By these measures, India has gained notoriety for being an unreliable supplier for international market denying its farmers their due benefits from participating in the international trade. Besides, the uncertainties regarding stocking norms, no investment worth its while can ever happen on scientific storage, processing, value addition and contract farming.

4.15 Conclusion

Increased agricultural sustainability can also be complementary to improvements in rural people's livelihoods. It can deliver increases in food production at relatively low cost, plus contribute to other important functions. Were these approaches to be widely adopted, they would make a significant impact on rural people's livelihoods, as well as on local and regional food security. But there are clearly major constraints to overcome. There will be losers along with winners, and some of the losers are currently powerful players. And yet, social organization and mobilization in a number of contexts is already leading to new informal and formal alliances that are protecting existing progress and developing the conditions for greater spread. Improving agricultural sustainability clearly will not bring all the solutions, but promising progress has been made in recent years. With further explicit support, particularly through international, national and local policy reforms, these benefits to food security and attendant improvements to natural, social and human capital could spread too much larger numbers of farmers and rural people in the coming decades. This empirical study shows that there have been promising advances in the adoption and spread of more sustainable agriculture. The 208 projects/initiatives show increases in food production over some 29 million hectares, with nearly 9 million households benefiting from increased food production and consumption. These increases are not yet making a significant mark on national statistics, as we believe there is a significant elasticity of food consumption in many poor rural households. They are eating the increased food produced, or marketing small surpluses to other local people.

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References

Aayog N (2015) Raising agricultural productivity and making farming remunerative for farmers. Occasional Paper NITI Aayog, Government of India, pp 1–46

Ahmed N (2008) Pesticide use in periurban environment. Introductory paper at the Faculty of Landscape Planning, Horticulture and Agricultural Science, Swedish University of Agricultural Sciences, pp 1–61

Alexandratos N (1999) World food and agriculture: outlook for the medium and longer term. Proc Natl Acad Sci U S A 96:5908–5914

Altieri MA (2018) Agroecology: the science of sustainable agriculture. CRC Press, Boca Raton, p 448

Altieri MA, Faminow MD (1996) Agroecology: the science of sustainable agriculture. Can J Agric Econ 44:199–201

Anderson RS, Levy E, Morrison B (1991) Rice science and development politics: Research strategies and IRRI's technology confront Asian diversity (1950-1980). Clarendon Press, Oxford

Aziz MA (2005) Country report, Bangladesh. Proceedings of the Asia regional workshop on the implementation, monitoring and observance of the international code of conduct on the distribution and use of pesticides, FAO of UN, pp 26–28

Balfour EB (1943) The living soil. Faber and Faber, London

Bartelmus P (1986) Environment and development. Allen & Unwin, London

Birdsey R, Cannell M, Galinski W, Gintings A, Hamburg S, Jallow B (2000) IPCC special report on land use, land-use change and forestry. Intergovernmental Panel on Climate Change, Geneva

Bond WJ (1998) Effluent irrigation—an environmental challenge for soil science. Soil Res 36:543–556

Bouwer H (2002) Integrated water management for the 21st century: problems and solutions. J Irrig Drain Eng 128:193–202
Bragg S (2005) Assessment of ‘win win’ case studies of resource management in agriculture. Environment Agency, London
Bunch R (1988) Case study 5: guinope integrated development program, Honduras. In: The greening of aid: sustainable livelihoods in practice. Earthscan, London, pp 40–44
Bunch R (1999) More productivity with fewer external inputs: Central American case studies of agroecological development and their broader implications. Environ Dev Sustain 1:219–233
Burney JA, Davis SJ, Lobell DB (2010) Greenhouse gas mitigation by agricultural intensification. Proc Natl Acad Sci 107:12052–12057
Byerlee D, Diao X, Jackson CP (2005) Agriculture, rural development, and pro-poor growth: country experiences in the post-reform era. Agriculture & Rural Development Department, World Bank, Washington, DC
Caporali F, Mancinelli R, Campiglia E (2003) Indicators of cropping system diversity in organic and conventional farms in Central Italy. Int J Agric Sustain 1:67–72
Carney D (1998) Sustainable rural livelihoods: what contribution can we make. Department for International Development, London
Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8:559–568
Carter H (1989) Agricultural sustainability: an overview and research assessment. Calif Agric 43:16–18
Cassman KG (1999) Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc Natl Acad Sci 96:5952–5959
Cassman KG, Pingali PL (1995) Intensification of irrigated rice systems: learning from the past to meet future challenges. GeoJournal 35:299–305
Cassman KG, Dobermann A, Walters DT (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. AMBIO: A J Hum Environ 31:132–140
Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Environ Resour 28:315–358
CGIAR (2015) Sustainable agriculture productivity growth and bridging the gap for small-family farms. Bioversity; CGIAR Consortium; Food and Agricultural Organization of the United Nations (FAO); International Fund for Agricultural Development (IFAD); International Food Policy Research Institute (IFPRI); Inter-American Institute for Cooperation on Agriculture (IICA); Organization for Economic Cooperation and Development (OECD); UN Conference on Trade and Development (UNCTAD); UN High Level Task Force on the Food Security Crisis; World Food Programme (WFP); World Bank; World Trade Organization (WTO)
Chand R (2017) Doubling farmers’ income rationale, strategy, prospects and action plan. NITI Policy Paper No. 1/2017, March
Charles D (2001) Seeds of discontent. Science 294:772–775
Cicerone RJ, Oremland RS (1988) Biogeochemical aspects of atmospheric methane. Global Biogeochem Cycle 2:299–327
Cohen JE, Fedoroff NV (1999) Colloquium on plants and population: is there time? Nat Acad Sci, Washington, DC
Coleman JS (1991) Grundlagen der Sozialtheorie. Band 1: Handlungen und Handlungssysteme, München/Wien
Conway G (1985) Agroecosystem analysis. Agric Adm 20:31–55
Conway G (1998) The doubly green revolution. Biologist Inst Biol 45:85–86
Conway GR, Pretty JN (2013) Unwelcome harvest: agriculture and pollution. Routledge, London
Costanza R et al (1997) The value of the world’s ecosystem services and natural capital. Nature 387:253
Cottingham R (2013) Case study 8 dry-season gardening projects, Niger. In: The greening of aid: sustainable livelihoods in practice. Earthscan, London, p 69
Council NR (1999a) Nature’s numbers: expanding the national economic accounts to include the environment. National Academy Press, Washington, DC

Council NR (1999b) Our common journey: a transition toward sustainability. National Academy Press, Washington, DC

Cox T, Picone C, Jackson W (2004) Research priorities in natural systems agriculture. J Crop Improv 12:511–531

Dalgaard T, Halberg N, Kristensen IS (1998) Can organic farming help to reduce N-losses. Nutr Cycle Agroecosys 52:277–287

Datt G, Ravallion M (1998) Farm productivity and rural poverty in India. J Dev Stud 34:62–85

DeVries J, Toenniessen GH (2001) Securing the harvest: biotechnology, breeding, and seed systems for African crops. CABI Publishing, New York

Dicks MR (1992) What will be required to guarantee the sustainability of US agriculture in the 21st century. Am J Altern Agric 7:190–195

Dirzo R, Raven PH (2003) Global state of biodiversity and loss. Annu Rev Environ Resour 28:137–167

Dobbs T, Becker D, Taylor D (1990) Sustainable agriculture policy analyses: south Dakota on-farm case studies. J Farming Syst Res Ext 2:109–124

Dobermann A, Cassman KG (2005) Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. Sci China Ser C Life Sci 48:745–758

Dobermann A, Nelson R, Beever D, Bergvinson D, Crowley E, Denning G, Giller K, d'Arros Hughes J, Jahn M, Lynam J (2013) Solutions for sustainable agriculture and food systems. United Nations sustainable development solutions network. France, Paris

Downing JA, Baker JL, Diaz RJ, Prato T, Rabalais NN, Zimmerman RJ (1999) Gulf of Mexico hypoxia: land and sea interactions. Task Force Rep 134:44

Dynesius M, Nilsson C (1994) Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753–762

El-Ashry MT, Duda AM (1999) Future perspectives on agricultural drainage. Agric Drain:1285–1298

Fan S, Hazell P, Thorat S (2000) Government spending, growth and poverty in rural India. Am J Agric Econ 82:1038–1051

FAO (2003) Fertilizer Requirements in 2015 and 2030. FAO, Rome

FAO (2005) Country report for Bangladesh. In Proceedings Asia regional workshop, implementation, monitoring and observance, International Code of Conduct on the distribution and use of pesticides, Bangkok, Thailand, 26–28 July 2005. RAP Publication 2005/29

Ferrier H, Shaw G, Nieuwenhuijsen M, Boobis A, Elliott P (2006) Assessment of uncertainty in a probabilistic model of consumer exposure to pesticide residues in food. Food Addit Contam 23:601–615

Fischer R, Edmeades GO (2010) Breeding and cereal yield progress. Crop Sci 50:S-85–S-98

Foresight U (2011) The future of food and farming. Final Project Report. The Government Office for Science, London

Francis CA, King JW (1988) Cropping systems based on farm-derived, renewable resources. Agric Syst 27:67–75

Galloway JN, Hiram Levy I, Kasibhatla PS (1994) Year 2020: consequences of population growth and development on deposition of oxidized nitrogen. Ambio 23(2):120–123

Ghassemi F, Jakeman AJ, Nix HA (1995) Salinisation of land and water resources: human causes, extent, management and case studies. UNSW Press/CAB International, Sydney/Wallingford

Gleick PH (1993) Water and conflict: fresh water resources and international security. Int Secur 18:79–112

Gliessman SR (2004) Integrating agroecological processes into cropping systems research. J Crop Improv 11:61–80

Gliessman SR (2005) Agroecology and agroecosystems. In: The Earthscan reader in sustainable agriculture. Routledge, London, pp 104–114

Godfray HC, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327(5967):812–818

Goodman D, Watts M, Watts MJ (1997) Globalising food: agrarian questions and global restructuring. Routledge, Landon

Gorbach SL (2001) Antimicrobial use in animal feed—time to stop. N Engl J Med 345:1202–1203

Green RE, Cornell SJ, Scharlemann JP, Balmford A (2005) Farming and the fate of wild nature. Science 307:550–555

Hall SJ, Matson PA, Roth PM (1996) NOx emissions from soil: implications for air quality modeling in agricultural regions. Annu Rev Energy Environ 21:311–346

Harrison P (1987) The greening of Africa. Breaking through in the battle for land and food. Paladin, London, p 215

Hatfield JL, Sauer TJ, Prueger JH (2001) Managing soils to achieve greater water use efficiency. Agron J 93:271–280

Hauptli H, Katz D, Thomas BR, Goodman RM (1990) Biotechnology and crop breeding for sustainable agriculture. Sustain Agric Syst:141–156

Helalia AM, El-Amir S, Abou-Zeid S, Zaghloul K (1992) Bio-reclamation of saline-sodic soil by Amshot grass in northern Egypt. Soil Tillage Res 22:109–115

Hesiod M, Morrissey C (1983) Theogony/works and days, shield. (trans: Athanassakis AN). The Johns Hopkins University Press, Baltimore/London

Hinchcliffe F, Thompson J, Pretty JN (1996) Sustainable agriculture and food security in east and Southern Africa. Report for the Committee on Food Security in East and Southern Africa, Swedish International Agency for International Cooperation, Stockholm

Hinchcliffe F, Thompson J, Pretty J, Guijt I, Shah P (1999) Fertile ground: the impacts of participatory watershed management. IT Publication, London

Howarth RW et al (1996) Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. In: Nitrogen cycling in the North Atlantic Ocean and its watersheds. Springer, Wallingford, pp 75–139

Irz X, Lin L, Thirtle C, Wiggins S (2001) Agricultural productivity growth and poverty alleviation. Dev Policy Rev 19:449–466

KangMin L (1992) Rice-fish farming systems in China: past, present and future. In: dela Cruz C, Lightfoot C, Costa-Pierce B, Carangal V, Bimbao M (eds) Rice-fish research and development in Asia, ICLARM Conf. Proc. 24. ICLARM, Manila, pp 17–26

Kesavan P, Swaminathan M (2008) Strategies and models for agricultural sustainability in developing Asian countries. Philos Trans R Soc Lond Ser B Biol Sci 363(1492):877–891

Kibblewhite M, Ritz K, Swift M (2008) Soil health in agricultural systems. Philos Trans R Soc Lond Ser B Biol Sci 363:685–701

Lamkin N (1994) Organic farming. Farming Press, Ipswich

Li W (2001) Agro-ecological farming systems in China, Man and the biosphere series, vol 26. UNESCO, Paris

Lobell DB, Cassman KG, Field CB (2009) Crop yield gaps: their importance, magnitudes, and causes. Annu Rev Environ Resour 34:179–204

Lockeretz W (1988) Open questions in sustainable agriculture. Am J Altern Agric 3:174–181

Løes A-K, Øgaard AF (2003) Concentrations of soil potassium after long-term organic dairy production. Int J Agric Sustain 1:14–29

MacRae RJ, Hill SB, Mehuys GR, Henning J (1990) Farm-scale agronomic and economic conversion from conventional to sustainable agriculture. In: Advances in agronomy, vol 43. Elsevier, Amsterdam, pp 155–198

Madden P (1987) Can sustainable agriculture be profitable? Environ Sci Policy Sustain Dev 29:18–34

Matson P, Billow C, Hall S, Zachariassen J (1996) Fertilization practices and soil variations control nitrogen oxide emissions from tropical sugar cane. J Geophys Res Atmos 101:18533–18545

Matson PA, Naylor R, Ortiz-Monasterio I (1998) Integration of environmental, agronomic, and economic aspects of fertilizer management. Science 280:112–115

McNeely JA, Scherr SJ (2001) Common ground, common future: how ecoagriculture can help feed the world and save wild biodiversity. IUCN, Washington, DC

McNeely JA, Scherr SJ (2003) Ecoagriculture: strategies to feed the world and save wild biodiversity. Island Press, Washington, DC

Mellor JW (2000) Faster more equitable growth: the relation between growth in agriculture and poverty reduction. Harvard Institute for International Development, Cambridge, MA

Meyer-Aurich A (2005) Economic and environmental analysis of sustainable farming practices–a Bavarian case study. Agricultural Systems 86:190–206

Minten B, Barrett CB (2008) Agricultural technology, productivity, and poverty in Madagascar. World Dev 36:797–822

Mintz SW, Du Bois CM (2002) The anthropology of food and eating. Annu Rev Anthropol 31:99–119

Morison J, Baker N, Mullineaux P, Davies W (2008) Improving water use in crop production. Philos Trans R Soc Lond Ser B Biol Sci 363:639–658

Muyanga M, Jayne TS, Burke WJ (2013) Pathways into and out of poverty: a study of rural household wealth dynamics in Kenya. J Dev Stud 49:1358–1374

Myers R, Palm C, Cuevas E, Gunatilleke I, Brossard M (1994) The synchronisation of nutrient mineralisation and plant nutrient demand. In: Woomer PI, Swift MJ (eds) The biological management of tropical soil fertility. Wiley-Sayce, Chichester/New York, pp 81–116

Naylor RL (1996) Energy and resource constraints on intensive agricultural production. Annu Rev Energy Environ 21:99–123

O'Connell PF (1990) Policy development for the low-input sustainable agriculture program. Sustain Agric Syst:453–458

Odum EP (1997) Ecology: a bridge between science and society. Sinauer, Sunderland

Oldeman LR (1992) Global extent of soil degradation. In: Bi-annual report 1991–1992/ISRIC. ISRIC, Wageningen, pp 19–36

Ortiz R (1998) Critical role of plant biotechnology for the genetic improvement of food crops: perspectives for the next millennium. Electron J Biotechnol 1:16–17

Oster J (2000) Irrigation sustainability. In: 6th international micro-irrigation congress (micro 2000), Cape Town, South Africa, 22–27 October 2000. International Commission on Irrigation and Drainage (ICID), pp 1–10

Oweis T (1999) Water harvesting and supplemental irrigation for improved water use efficiency in dry areas, Vol 7. IWMI, Colombo, Sri Lanka

Palumbi SR (2001) Humans as the world's greatest evolutionary force. Science 293:1786–1790

Peng S, Garcia F, Laza R, Sanico A, Visperas R, Cassman K (1996) Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crop Res 47:243–252

Pimentel D, Krummel J, Gallahan D, Hough J, Merrill A, Schreiner I, Vittum P, Koziol F, Back E, Yen D, Fiance S (1978) Benefits and costs of pesticide use in US food production. Bioscience 28:772–784

Pimentel D, Acquay H, Biltonen M, Rice P, Silva M, Nelson J, Lipner V, Giordano S, Horowitz A, D'amore M (1992) Environmental and economic costs of pesticide use. Bioscience 42:750–760

Pimentel D, McLaughlin L, Zepp A, Lakitan B, Kraus T, Kleinman P, Vancini F, Roach WJ, Graap E, Keeton WS, Selig G (1993) Environmental and economic effects of reducing pesticide use in agriculture. In: Agriculture and the environment. Elsevier, Amsterdam, pp 273–288

Pinstrup-Andersen P, Pandya-Lorch R (1996) Food for all in 2020: can the world be fed without damaging the environment. Environ Conserv 23:226–234

Postel S (1999) Pillar of sand: can the irrigation miracle last. WW Norton, New York

Postel SL, Daily GC, Ehrlich PR (1996) Human appropriation of renewable fresh water. Science 271:785–788

Pretty JN (1995) Regenerating agriculture: policies and practice for sustainability and self-reliance. Joseph Henry Press, Washington, DC

Pretty J (2005) The Earthscan reader in sustainable agriculture. Earthscan, London

Pretty J, Ball A (2001) Agricultural influences on carbon emissions and sequestration: a review of evidence and the emerging trading options. Centre for Environment and Society occasional paper 3, p 31

Pretty J, Hine R (2005) Pesticide use and the environment. Earthscan, London

Pretty J, Uphoff N (2001) Human dimensions of agroecological development. Earthscan, London
Pretty J, Waibel H (2005) Paying the price: the full cost of pesticides the pesticide detox. Earthscan, London, pp 39–54
Pretty J, Ward H (2001) Social capital and the environment. World Dev 29:209–227
Pretty JN, Morison JI, Hine RE (2003) Reducing food poverty by increasing agricultural sustainability in developing countries. Agric Ecosyst Environ 95:217–234
Putnam RD, Leonardi R, Nanetti RY (1994) Making democracy work: civic traditions in modern Italy. Princeton University Press, Princeton
Qadir M, Oster J (2002) Vegetative bioremediation of calcareous sodic soils: history, mechanisms, and evaluation. Irrig Sci 21:91–101
Raka S, Singh N, Balaji S, Ahuja U, Deepika J (2017) Strategy for doubling income of farmers in India. Policy paper-National Centre for Agricultural Economics and Policy Research strategy for doubling income of farmers in India. Policy paper 31
Rengasamy S, Devavaram J, Prasad R, Erskine A, Balamurugan P, High C (2000) The land without a farmer becomes barren (thaan vuzhu nilam thariso), Speech, Ezhil Nagar, Madurai, India
Rhoades J (1999) Use of saline drainage water for irrigation. 1 vol agriculturaldra. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America
Robertson GP (1997) Nitrogen use efficiency in row-crop agriculture: crop nitrogen use and soil nitrogen loss. Ecol Agric:347–365
Rodale R, Wagner R (1990) Finding the middle of the road on sustainability. J Prod Agric 3:273–280
Ruttan VW (1999) The transition to agricultural sustainability. Proc Natl Acad Sci 96:5960–5967
Ruttan VW (2002) Productivity growth in world agriculture: sources and constraints. J Econ Perspect 16:161–184
Sandra P (1997) Last oasis, facing water scarcity. WW Norton, New York
Scherr SJ, McNeely JA (2008) Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture' landscapes. Philos Trans R Soc Lond Ser B Biol Sci 363:477–494
Scoones I (1998) Sustainable rural livelihoods: a framework for analysis. Working Paper 72, Institute for Development Studies, Brighton, UK
Seckler D, Barker R, Amarasinghe U (1999) Water scarcity in the twenty-first century. Int J Water Resour D 15:29–42
Sendhil R, Kumar A, Singh S, Chatrath R, Singh G (2017a) Framework for doubling the income of wheat producers' by 2022: trends, pathway and drivers. Indian J Econ Dev 13:1–8
Sendhil R, Ramasundaram P, Balaji S (2017b) Transforming Indian agriculture: is doubling farmers' income by 2022 in the realm of reality. Curr Sci 113:848
Shah P, Shah MK (1999) Institutional strengthening for watershed development: the case of the AKRSP in India fertile ground: the impacts of participatory watershed development. IT Publication, London
Shalhevet J (1994) Using water of marginal quality for crop production: major issues. Agric Water Mange 25:233–269
Sharma I, Chatrath R, Sendhil R (2013) Challenges, target and strategies for sustainable wheat production for food security and nutrition. Indian Farming 63
Shiva V (1991) The violence of the Green Revolution. Third world agriculture, ecology, and politics, The other India, Goa
Smil V (1999) Nitrogen in crop production: an account of global flows. Global Biogeochem Cycle 13:647–662
Smith KE et al (1999) Quinolone-resistant campylobacter jejuni infections in Minnesota, 1992–1998 New England. J Med 340:1525–1532
Stinner BR, House GJ (1987) Role of ecology in lower-input, sustainable agriculture: an introduction. Am J Altern Agric 2:146–147
Stinner BR, House GJ (1989) The search for sustainable agroecosystems. J Soil Water Conserv 44:111–116

Swaminathan M (1999) A century of hope: towards an era of harmony with nature and freedom from hunger. East West Books (Madras) Pvt. Ltd, Chennai
Swaminathan M (2000) Towards an evergreen revolution in agriculture. Nutr News 8:8
Swift MJ, Izac AM, Van Noordwijk M (2004) Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions. Agric Ecosyst Environ 104:113–134
Tilman D et al (2001) Forecasting agriculturally driven global environmental change. Science 292:281–284
Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418:671
Timmer CP (1995) Getting agriculture moving: do markets provide the right signals. Food Policy 20:455–472
Tomich TP et al (2004) Policy analysis and environmental problems at different scales: asking the right questions. Agric Ecosyst Environ 104:5–18
Travisi CM, Nijkamp P, Vindigni G (2006) Pesticide risk valuation in empirical economics: a comparative approach. Ecol Econ 56:455–474
Trewavas A (2002) Malthus foiled again and again. Nature 418:668
Uphoff N (2000) Understanding social capital: learning from the analysis and experience of participation social capital: a multifaceted perspective. UNSW Press/CAB, Sydney/Wallingford, pp 215–249
Uphoff N (2002) Agroecological innovations. Earthscan, London
Varshney A (1998) Democracy, development, and the countryside: urban-rural struggles in India. Cambridge University, Cambridge
Vitousek PM, Matson PA (1993) Agriculture, the global nitrogen cycle, and trace gas flux. In: Biogeochemistry of global change. Springer, Boston, pp 193–208
Vitousek PM et al (1997a) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737–750
Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997b) Human domination of Earth's ecosystems. Science 277:494–499
Wallace J (2000) Increasing agricultural water use efficiency to meet future food production. Agric Ecosyst Environ 82:105–119
Weil RR (1990) Defining and using the concept of sustainable agriculture. J Agron Educ 19:126–130
WHO (1990) Public health impact of pesticides used in agriculture. WHO, Geneva (in preparation)
Wichelns D (2002) An economic perspective on the potential gains from improvements in irrigation water management. Agric Water Manag 52:233–248
York E (1991) Agricultural sustainability and its implications to the horticulture profession and the ability to meet global food needs. HortScience 26:1252–1256
Zandstra H (1994) Sustainability and productivity growth: issues, objectives and knowledge needs. Guidelines for working groups. Reconciling Sustainability with Productivity Growth. Report of a workshop, Gainesville, Florida, May 1993, University of Florida and Cornell University

Integrated Soil Fertility Management

5

Sarita K. Yadav and Ruchi Soni

Abstract

Soil is an organic thin layer of earth's crust, a living media. Soil is the basis entity for farming, without which farming can't be practiced. The human greed has led to the exploitation of the soil to a great extend in the recent times. Soil fertility depletion and soil quality decline have been threatening the ecological and economic sustainability of crop production. This is the major concern for the sustainability of Indian agriculture. This has made the soil exposed to excess chemicals in the form of fertilizers, insecticides, pesticides etc. Integrated Soil Fertility Management involves the use of both chemicals and organic matter. Agronomic practices are also to be followed by taking care of plant densities and weeding, so that nutrients can be used efficiently. World has been observing World Soil Day on December 5 to maintain the optimum level of soil health. In this lieu, United Nations General Assembly declared 2015 as International Year of Soils, creating awareness amongst the stakeholders and to promote sustainable use of soil.

Keywords

Soil · Soil management · Soil health · World soil day

5.1 Introduction

In carrying out sustainable agriculture, deterioration in the fertility of the soil is a major concern. Maintaining optimum soil fertility, Indian farmers, have been practicing agricultural system which ensures modest and stable yields. The increased

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population has led to the introduction of high yielding varieties of seeds, intensive excess of chemical fertilizers, pesticides and extensive tillage. India is highly affected by land degradation. Rain-fed areas are seriously affected by land degradation.

Year 2005 was declared as International Year of Soil with the following objectives to be achieved:

- (i) To generate awareness among society and decision-makers the vitality of soil in human life.
- (ii) Provide education to public about the role of soil in food security, climate change adaptation and mitigation, essential ecosystem services, poverty alleviation and sustainable development.
- (iii) Enact according to the policies and programs for the sustainable management and protection of soil resources.
- (iv) To adapt sustainable soil management activities to develop and maintain healthy soils for various land users and population groups.
- (v) With a well planned process of Sustainable Development Goals initiatives should be carried out.
- (vi) Rapid capacity enhancement for soil information collection and monitoring should be taken care at the regional, national and global level (Patel 2016).

It is to be remembered that all stakeholders associated with agriculture all over the world have to put in all the efforts to promote scientific management of soil resources for soil protection, conservation and sustainable productivity. This goal can be achieved by (i) consider technical cooperation and investment in R & D from all over the globe. (ii) targeted soil research and development is to be focused on identified gaps and priorities (iii) Quantity and quality of soil data and information is to be enhanced: data collection (generation), analysis, validation, reporting, monitoring and integration with other disciplines (iv) novel methods, measurements and indictors for the sustainable management and protection of soil resources. (v) initiation of policies and programs to educate farmers and create awareness to promote regenerative landscape and integrated management of soil and other natural resources viz., water, vegetation. Biodiversity is also to be taken care of to be able to achieve sustainable agricultural production that is good for the environment and farm profits (Patel 2016).

For the recovery of soil health, Integrated Soil Fertility Management (ISFM) has to be adopted. The involvement of both chemical fertilizers and organic matter (crop residue, compost and green manure) along with the practices of crop rotation and legumes as inter-crops (crop which fix atmospheric nitrogen) can lead to improvised soil health (Mundt 2002; Srinivasarao et al. 2012; Kumar 2017). Also studies carried out in recent times have found that the application of combined inputs and practices can almost double the crop yield compared to fertilizers applied separately (Agegnehu and Bekele 2005; Våje 2007; Dercon and Hill 2009). India along with other various countries has seen soil fertility decline as a major problem (Sanchez et al. 1997; Bationo et al. 2006; Sanginga and Woomer 2009; Vanlauwe et al. 2010).

5.2 Characteristic Features of Soil

Soil is habitat for various living organisms which interact amongst themselves and are responsible for the life which exist on this planet. Living organisms of the soil control water infiltration, mineral density and nutrient cycling. Microorganisms fungi and bacteria associate with organic matter in the soil to break it down into yet smaller molecules, earthworms digest organic matter, recycle nutrients and thus makes the surface soil richer. Along with the living component soil has minerals and nutrients. Carbon is one of the most important variable within the soil, which assists in many processes like development of soil structure, water storage and nutrient cycling. Soil carbon is available in three forms, viz., living carbon, labile carbon and fixed carbon. Microbes, plant roots, nematodes, earthworms etc. belong to living carbon. Labile carbon comprises of stable compounds as humates and glomalins. Sequestered carbon includes the fixed carbon plus the total living biomass. If soil possesses high organic carbon content then rainfall infiltration and retention is enhanced. Although, it takes around 500 years for the formation of top soil, soil erosion happens at a much faster rate. To produce nutritionally dense food, structural, biological and mineral health of the soil (N, P, K) should be considered (Patel 2016).

5.3 Soil: Our Vital Resource

Soil is one of the most complex biological materials on our planet. Soils are responsible for 95% of our food. 10% of the total CO_2 emitted is stored in soil. If scientifically composted, half of the kitchen waste could have nurtured our soil. Being a reservoir for minerals, organic matter, water and air, it provides a complete balance of nutrients for plant growth. Food, feed, fuel, fibre, water and medicinal/herbal products are important for human well-being. Soils play an important role in the carbon cycle. Soil also happens to be largest pool of organic carbon, which is the key factor in mitigating and adapting to climate change. It also turns out to be the appropriate for storage and distribution of water. According to FAO, a third of all soils are degraded due to erosion, compaction, soil sealing, salinization, depletion of soil organic matter and nutrients, acidification, pollution and other processes caused by unsustainable land management practices. Even if scientific approaches are researched and adopted, the global amount of arable and productive land per person in 2050 will be only one-fourth of the level it was in 1960. Hence, it is must for policy makers and farmers to appreciate soil functions and assess the risks it is running right now (Patel 2016).

5.4 Status of Indian Soil

About 18% of world's human population and 15% of livestock population is reared in India possessing just 2% of world's geographical area and 1.5% of forest and pasture land. In India out of a total of 328.7 million hectares (MHA), 142 MHA are net cultivated area. Out of this 40%, i.e. 57 MHA are irrigated and rest 60% i.e. 85 MHA are rain-fed. Out of 328.7 MHA about 120.4 MHA (37%) suffer from various kinds of land degradation, viz., water and wind erosion (94.9 MHA), water logging (0.9 MHA), soil alkalinity/sodicity (3.7 MHA), soil acidity (17.9 MHA), soil salinity (2.7 MHA) and mining and industrial waste (0.3 MHA). Intensive agriculture, greater mining of nutrients has led to deplete the soil fertility and deficiencies of secondary and micronutrients, depleting water table level and its quality. These all have caused soil erosion and degradation to such an extent that only proper methodologies, technologies and awareness can bring this resource somewhere near to the naïve soil (Anonymous 2016a; Patel 2016).

5.5 Causes and Management of Soil Degradation

Ever-growing demands of the growing population for food, fodder and fibre has led to the excessive pressure on land, further degrading the soil quality. Without investigating the chemistry and status of the soil, nutrients like nitrogen, phosphorus and potassium have been applied indiscriminately to the arable soil. This leads to the imbalances due to excess of certain nutrients and deficiency of another (Dhok and Metkari 2011).

Large scale irrigation canals, deforestation and removal of natural vegetation, agriculture related activities, overgrazing, over exploitation of vegetation for domestic purpose, flawed use of land led to various soil problems like salinization, flooding, drought, erosion and waterlogging. In turn, these processes reduced agricultural productivity leading to social insecurity. Global warming due to the emission of greenhouse gases is also a major cause for soil degradation.

5.5.1 Soil Erosion

This is the most common and major factor responsible for the degradation of natural resources.

Soil erosion remains one of the most prevalent problem since ancient times. This was recognized by the British government using 1930s (Shah 1997; Reddy et al. 2004). In mountainous regions, soil erosion is more severe than in plains. Practicing inappropriate methods for hilly regions like tilling along the slope, lack of crop cover during heavy rainfall etc. makes the erosion severe (Basu et al. 1960; Vittal et al. 1990). Soil degradation is through the loss of topsoil which results in the production of low and unstable crop yields in rainfed semiarid to sub-humid subtropics of India (Vittal et al. 1990). Wind causes erosion in the arid and semiarid regions of India, which includes Rajasthan, Haryana, Gujarat and Punjab. This type of erosion is called wind erosion which is enhanced by removal of natural vegetative cover resulting from excessive grazing and extension of agriculture to the marginal areas (Sidhu et al. 2010; Sidhu et al. 2013).

5.5.2 Slaking and Dispersion

Slaking and dispersion leads to the mechanisms of soil structural collapse and degradation, which in turn changes soil from one type to another (Dhruvanarayana and Babu 1983). Slaking happens when there is a breakdown of aggregates into smaller aggregates or single particles. Usually the process occurs when the dry clay becomes wet. This makes the clay to swell and the air within the pore spaces aggregates is compressed, resulting in pressure which leads to explosion of the aggregates. Addition of organic matter helps in the reduction of slaking by reduction in the rate of aggregate wetting and by more strongly binding the soil particles together.

The separation of clay particles from the aggregates when the soil is wet is called dispersion. Usually lime is used to avoid the problem of dispersion (Moody and Cong 2008).

5.5.3 Salinization and Alkalization

The enhancement in irrigation amenities has enabled to achieve efficiency in food production. This resulted in an increase of net irrigated area in India from 22 M ha in 1950 to about more than 68.2 M ha in 2016. Although this expansion helped to achieve targets of higher production, but made the level of groundwater level to rise. In turn, it made the soil to deteriorate through accumulation of salts (Abrol and Bhumbla 1971; Anonymous 2016b).

5.5.4 Acidity

Most of the acid soils in India belong to laterites and latosolic soils eg. Ferruginous red soils, ferruginous gravelly red soils, mixed red and black, or red and yellow soils. About 6.98 M ha area is affected by acid soils, which is about 9.4% of total geographic area. Acid soils develop in humid and per humid areas. There are various problems caused due to acidic soils, which are mostly associated with physical and chemical properties and chemical properties. Kaolinite dominated light textured acid soils have very high saturated hydraulic conductivity leading to heavy percolation losses. The efficiency of these soils can be enhanced by light and frequent irrigation practices. Mulching of crop lands with paddy straw can be done to reduce the problems of high evaporative demands on crusting soils. Mulching reduces the loss of water by evapo-transpiration, thus saves irrigation water up to 15–20% depending up on the crop. Incorporation of paddy husk and powdered groundnut shells followed by light irrigation can avoid hardening of red loamy soils. This technique retains moisture in the soil for a longer time can be carried over for rabi crops. Poor water efficiency is due to poor aggregate stability. Stability of aggregates can be achieved by application of compost, paddy straw and green manuring. Liming followed by light irrigation is the most effective technique, which helps in achieving improved chemical and biological properties of acid soils and increase water use efficiency (Maji et al. 2008).

5.5.5 Reduction in Organic Carbon

Pedogenic processes are responsible for the chemical deterioration of Alfisols, Ultisols and Oxisols leading to nutrient depletion. In India about 3.7 M ha land is deteriorated due to reduction of organic matter. In-situ burning of crop residues or their removal, no or least addition of organic residues and intensive agriculture leads to the depletion of soil organic carbon. Use of balanced and integrated inorganic and organics, proper management of crop residues, etc. are desirable options for sequestering organic carbon in soils (Aulakh 2011).

5.5.6 Nutrient Imbalance

To achieve high crop yields, balanced nutrient supply is essential, but nutrient loss happens in various forms, viz., NH_3, N_2O, NO and N_2 and discharge to water through runoff, leaching and erosion. During the green evolution era the usage of fertilizers increased drastically in agriculturally developed states like Punjab and Haryana to cope up the increasing demand of the ever growing population and nature of hybrid varieties. In high intensive cultivated areas of rice-wheat cropping system in Indo-Gangetic Plains poor soil health has been studied. With the incorporation of both fertilizers and organic manures, N imbalance and N losses can be improvised without sacrificing the crop yield (Aulakh 2011).

5.5.7 Pollution Caused by Toxic Substances

The impact of pollution varies depending on the rainfall pattern, depth and geology of aquifer. This is true in cases of both geogenic and anthropogenic factors responsible for causing pollution. Aquitards are the naturally occurring minerals in different regions, which control the concentration of geogenic pollutants such as arsenic (As), uranium (Ur), fluoride (F), boron (B) and selenium (Se) in alluvial aquifers. In most of the cases as is found in drinking groundwater. pH, oxidation-reduction, associated or competing ions are the geochemical properties which along with evaporative environments have significant effects on As concentration in groundwater. Oxi-hydroxides of iron conrol the conditions of metals in aquifers or surface waters in natural conditions. Iron precipitates as hematite gets deposited on the surface of particulate suspensions under oxidized conditions (Goswami 2005). Environmental pollution such as eutrophication arise when excessive fertilizers used are washed to the water bodies. Minerals like fluoride, boron and nitrate pose a major environmental hazard. According to a WHO report, the permissible limits for fluoride, boron and nitrate are 1.5, 1 and 45 ppm respectively (Patel 2016). In India and China fluorosis is the most severe and widespread. Seventeen states of India are endemic with fluorosis cases to be around 66 million (UNICEF 1999). Phytoremediation plays an important role in the controlling and decreasing toxins from the soils. The use of plants is the simplest and cost effective method in terms of technology (Bavandi 1975; Beeton 1969; Alkorta and Garbisu 2001; Alkorta et al. 2004; Khakbaz et al. 2012).

5.5.8 Soil Sealing and Capping

The never ending desire of human has led to the continuous expansions of fertile and productive soils. This leads to the drastic and often irreversible land use changes such as conversion of forest to agro-industrial land, extractive mining activities, as well as extensive horizontal expansion of cities have been resulting in the soil sealing and capping. Options like vertical expansion rather than horizontal, adoption of apartment system in place of bungalows etc. Waste and unproductive soils would be used for the establishment of new cities and industries. Artificial, impenetrable surfaces interfere with the essential environmental, economic and social functions performed by soil (Sutton et al. 2009).

5.6 Programs on Soil Management

Soil is a non-renewable resource, thus policies, strategies and the processes regarding the use of soil have to be formed. For a food-secure world, FAO and its members initiated the Global Soil Partnership (GSP) to improve governance of the soil resources. Soil being a limited resource, has to be used judiciously, hence formation of coherent policies with the implementation of standard practices and methods have to be followed so that the soil usage can be regulated. Scientific techniques in agriculture such as practices for tillage, fertilizer application and crop rotation have to be adopted so that soil fertility, structure and carbon sequestration can be maintained. Use of latest technologies with the involvement of Geographical Information System (GIS) and remote sensing a global/national soil map can be created to represent different soil types. Through mapping and web-based software, GIS is used to display, analyze and collect soil data and processes, so that different types of soils can be identified (Patel 2016).

For the first time since India's independence in 11th five year plan (2007–2012) importance of proper soil management was acknowledged. Soil Health Cards Program was developed in 2006 for betterment of farmers' knowledge on soil and soil management practices. The soil profile received after analysis of soil, farmers receive current status of their soil. Accordingly most suitable fertilizers can be applied without further harming the soil and providing the suitable required nutrient to the soil. This program was piloted in Gujarat and later on to other states to drastically improve the available database on soil. Due to the success of this scheme its implementation has been done at national level. To carry out this schemes a number of soil testing labs have been established, the soil samples are diagnosed in large numbers (Patel 2016).

5.7 Socio-Economic Impacts and Future Challenges

It is seen commonly that severely degraded lands are mostly inhabited by marginal farmers and tribal populations, who are poor and less literate. Due to poor soil the farmers are forced to find out more agri-land, hence converting forest area into cultivatable land, thus reducing the forest area. Or else farmers try to get marginal boost in the yield by application of surplus fertilizers, which in turn further depletes the condition of the soil. This whole scenario seems to be a vicious circle from which it is impossible to escape. Soil scientists and environmentalists are making an effort to evaluate the precise magnitude of soil degradation and its impact on the environment. Fields of science and farming, both require their due innovations so that the goals are achieved. Apart from this the natural resource data, soil status also should be made available from the remote sensing satellites. This would provide characterization of natural resources including soil and conserve the natural resources and rejuvenate the degraded wastelands, which offer potentially enormous means of poverty alleviation and sustainable livelihood (Reddy et al. 2004).

5.8 Conclusion and Future Prospective

All over the world, soil health has been identified as a major concern. Governments have initiated certain programs for the benefits of farmers. At the same time scientists are trying to use available techniques and tools at their best to improve the soil health as well as reclaim the lost land. With the use of proper methodology, techniques and programs we can surely succeed. Thus integrated soil fertility management will enhance our land fertility, productivity and yield, which will provide us the scope of pulling our population out of poverty and distress.

References

Abrol IP, Bhumbla DR (1971) Saline and alkali soils in India – their occurrence and management. Paper presented at FAO-UNDP seminar "Soil Fertility Research". FAO World Soil Resources Report No. 41: 42–51

Agegnehu G, Bekele T (2005) On-farm integrated soil fertility management in wheat on Nitisols of central Ethiopian highlands. Ethiop J Nat Resour 7:141–155

Alkorta I, Garbisu C (2001) Phytoremediation of organic contaminants. Bioresour Technol 79:273–276

Alkorta I, Hernăndez-Allica J, Becerril JM, Amezaga I, Albizu I, Garbisu C (2004) Recent findings on the phytoremediation of soils contaminated with environmentally toxic heavy metals and metalloids such as zinc, cadmium, lead, and arsenic. Rev Environ Sci Biotechnol 3:71–90

Anonymous (2016a) Annual report of Department of Agriculture, Cooperation and Farmers' Welfare, Ministry of Agriculture Farmers' Welfare, pp 194

Anonymous (2016b) Annual report of Indian Institute of Soil Science, Bhopal

Aulakh MS (2011) Integrated soil tillage and nutrient management – the way to sustain crop production, soil-plant-animal-human health, and environment. J Indian Soc Soil Sci 59:S23–S34

Basu JK, Kaith DC, Rao R MSU (1960) Soil conservation of India. Farm Bulletin 58, Farm Information Unit, Directorate of Extension, Ministry of Food and Agriculture, New Delhi, 64 pp

Bationo A, Hartemink A, Lumgu O, Naimi M, Okoth P, Smaling E, Thaiombiano L (2006) African soils: their productivity and profitability of fertilizer use. Africa Fertilizer Summit, Abuja

Bavandi B (1975) Ecosystem, Publications of the Department of the Environment (DoE)

Beeton AM (1969) Changes in the environment and biota of the great lakes. In: Eutrophication: causes, consequences, corrective, symposium. National Academy of Science, Washington, DC

Dercon S, Hill RV (2009) Growth from agriculture in Ethiopia. Identifying key constraints: paper prepared as part of a study on agriculture and growth in Ethiopia. DFID, UK

Dhok SP, Metkari P (2011) Integrated soil fertility management for sustainable agriculture. Integrated soil management. Rashtryia Krishi 6(1):82–83

Dhruvanarayana VV, Babu R (1983) Estimation of soil erosion in India. J Irrig Drain Eng ASCE 109(4):419–434

Goswami NN (2005) Soil and its quality vis-à-vis sustainability and society: some random thoughts. In: Proceedings of international conference on soil, water and environmental quality issues and strategies. Indian Society of Soil Science, New Delhi, pp 43–58

Khakbaz PP-P, Mahdeloei S, Heidari A (2012) Soil pollution control management techniques and methods. Ann Biol Res 3(7):3101–3109

Kumar P (2017) Integrated soil fertility management: converting subsistence farming to productive farming. Newsreach. Nov–Dec. 19–23

Maji AK, Obi Reddy GP, Meshram S (2008) Acid soil map of India. Annual Report National Bureau of Soil Survey and Land Use Planning, Nagpur

Moody PW, Cong P (2008) Soil constraints and management package (SCAMP): guidelines for sustainable management of tropical upland soils, ACIAR Monograph No. 130, pp 86

Mundt (2002) Use of multiline cultivars and cultivar mixtures for disease management. Annu Rev Phytopathol 40:381–410. https://doi.org/10.1146/annurev.phyto.40.011402.113723

Patel A (2016) Addressing soil health management issues in India. Int J Manag Granthaalayah 4(12):110–123

Reddy BVC, Hoag D, Shobha BS (2004) Economic incentives for soil conservation in India. Conserving soil and water for society: Sharing solutions. 13th international soil conservation organisation conference – Brisbane, July

Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Izac MN, Mokwunye AU, Kwesiga FR, Ndiritu CG, Woomer PL (1997) Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa, SSSA Special Publication No. 51. SSSA, Madison, pp 1–46

Sanginga N, Woomer PL (2009) Integrated soil fertility management in Africa: principles, practices and developmental process. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture, Nairobi, p 252

Shah A (1997) Soil water conservation in India and Africa: reflections on environment –development perspectives. In: Dhaliwa GS, Randhawa NS, Arora R, Dhawan AK (eds) Ecological agriculture and sustainable development, vol 1. Digi Graphics, New Delhi, pp 199–210

Sidhu GS, Yadav RP, Singh SP, Sharma JP, Aggarwal RK, Tiwari AK, Gajbhiye KS, Sarkar D, Sharda VN (2010) Soil erosion in Himachal Pradesh, NBSS Publication 132. National Bureau of Soil Survey and Land Use Planning, Nagpur, p 53

Sidhu GS, Sharmistha P, Tiwari AK, Sarkar D, Sharda VN (2013) Soil erosion in Punjab, NBSS Publication 151. National Bureau of Soil Survey and Land Use Planning, Nagpur, p 33

Srinivasarao C, Venkateswarlu B, Lal R (2012) Long-term effects of soil fertility management on carbon sequestration in a rice-lentil cropping system of the Indo-Gangetic plains. Soil Sci Soc Am J 76(1):167–178

Sutton PC, Anderson SJ, Elvidge CD (2009) Paving the planet: impervious surface as proxy measure of the human ecological footprint. Prog Phys Geogr 33:510–527

UNICEF (1999) States of the art report on the extent of fluoride in drinking water and the resulting endemicity in India. Report by Fluorosis and Rural Development Foundation for UNICEF, New Delhi

Våje PI (2007) Soil fertility issues in Blue Nile Valley, Ethiopia. Advances in integrated soil fertility management in Sub-Saharan Africa: challenges and opportunities. Springer Publishing, Dordrecht, pp 139–148

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD, Smaling MA, Woomer PL, Sanginga N (2010) Integrated soil fertility management operational definition and consequences for implementation and dissemination. Outlook Agric 39:17–24

Vittal KKR, Vijayalakshmi K, Rao UMB (1990) The effect of cumulative erosion and rainfall on sorghum, pearl millet, and castor bean yields under dry farming conditions in Andhra Pradesh, India. Exp Agric 26:429–439

Soil Quality Status in Different Region of Nepal

6

Anup K C and Ambika Ghimire

Abstract

Soil is a complex mixture of organic matter, water, air, minerals, and living things formed after the chemical disintegration of rock fragments. Soil quality is the interaction of physical, chemical and biological properties for agricultural practices and other activities performed in the soil. This book chapter focuses on methodological issues and observations on soil quality status in the global and Nepalese perspectives. Different researchers have used different methodologies for assessing soil quality. Most of them have focused on measuring physical, chemical and biological parameters by using standard methodologies and deciding soil quality status thereafter. Different land use patterns (forest land, grass land, agricultural land, and residential areas) have different quality of soil in their different altitude, slope aspects, and soil types. They have observed that use of modern and conservation type farming practices have helped to minimize soil erosion in hill slopes and other agricultural fields, conserve the physical, chemical and biological properties of soil, and increase the crop productivity. It is necessary to minimize anthropogenic activities on soil to maintain soil quality status of any type of soil. Regular monitoring of soil quality is also important to conserve its quality, increase agricultural output, and income, and enhance the standard of living of the agricultural dependent people.

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Soil quality · Biological property · Methodologies · Land use pattern · Crop productivity · Anthropogenic activity

6.1 Introduction

Soil is a combined form of inorganic minerals, organic matter, air, water, and living matter which is present at the top layer of crust and helps in the growth of plants (K C and Kalu 2015). It remains different in its properties from original combination due to the interaction of several climatic, biological and environmental parameters (Manimegalai and Sukanya 2014, K C et al. 2013). Also, varieties of soil are identified in the world due to the difference in soil formation process. It is categorized on the basis of different physical (soil texture, color, grain size distribution), chemical (pH, heavy metals, organic matter, and inorganic nutrients) and biological characteristics (microorganisms, floral and faunal diversity) (K C and Kalu 2015). It is also categorized for the purpose of land use planning, agricultural diversification, and development planning (Bajracharya et al. 2007).

6.2 Soil Quality

Soil quality is an important criteria which helps to maintain the productivity of plants and animals, balance the air and water content, and enhance living and well-being of a person in any kind of natural and manmade conditions (Karlen et al. 1995). If the soil is of good quality, it can provide essential minerals for the growth of vegetation. It can be affected by the use of synthetic fertilizers, pesticides, and presence of flora and fauna (Addis and Abebaw 2014). To sustain the production from farming activities, it is necessary to balance various nutrients present in the soil. Quality of soil can be restored by preserving important physiochemical and biological parameters. Basic parameters affecting quality of soil are carbon, nitrogen, phosphorus, potassium, pH, soil moisture, soil texture, and other heavy metals (K C et al. 2013) (Fig. 6.1).

Most of the physical and chemical parameters of soil vary across slope aspect, location and topography (Begum et al. 2010). Degree of hotness and coldness, and rainfall data vary with the altitudinal gradient and physiochemical parameter of soil has direct association with the slope. Soil organic matter decomposition is affected by change in altitude, temperature and moisture. Change in elevation affect carbon in soil by maintaining geologic deformation procedure, soil erosion, soil water balance, species and biomass generation of the local vegetation and cultivated plants (Griffiths et al. 2009). Other factors influencing properties of soil are moisture, temperature, humidity and soil pH. Carbon and nitrogen content, and other soil nutrients increases with increase in humidity while biotic factors and biomass composition are affected by soil pH and other soil chemicals (Saeed et al. 2014).

Fig. 6.1 Forest soil with sufficient water availability in Panchase, Nepal

6.3 Soil Quality Assessment

Soil quality is determined by combination of micronutrients and macronutrients in relation to its productivity. Soil health and ecological functions are determined by soil organic carbon, animal diversity, plant biomass and diversity of plant species (Bajracharya et al. 2007). Assessment of soil quality can be done to assess the process of soil formation as well as to see the proper functioning of the soil. It can be done by assessing the current state of the soil and comparing it with previous results or some other standards (Karlen et al. 1995). Beside this, systematic techniques should be applied to observe the socio-economic parameters such as water availability, food hygiene, recreational benefits and biodiversity conservation (Karlen et al. 1995). Knowledge about the fertility status of soil can help to identify appropriate crop or vegetation and achieve higher productivity (K C et al. 2013). There is very less information on the quality of soil in least developed countries (Addis and Abebaw 2014). Regular studies are necessary to assess the performance of the soil and to maintain the natural resource productivity in the land (Karlen et al. 1995).

Different techniques are applied to assess and sustain the soil quality status of a particular soil. Agriculture in the hills and slope and use of chemical fertilizers and pesticides is a major challenge for maintaining soil quality (K C et al. 2013). Agroforestry system improves soil quality and provides suitable condition for the growth of plants as compared to conventional farming techniques. It provides benefit from ecological services (soil erosion control, carbon absorption, air and water purification, increasing floral and faunal diversity, and improving natural beauty) and conserve land productivity (increase farm products, crops, income, and economic condition) (Schwab et al. 2015) (Fig. 6.2).

Fig. 6.2 Agricultural terraces in the lower elevation near Adhikhola river, Nepal

6.4 Methods of Soil Quality Assessment in the Global Context

Different researchers are implementing different techniques for determining and maintaining soil quality in global and Nepalese perspectives. Chemical and physical properties determination in the laboratory and biological assessment in the field are the main aspects of soil quality determination. Some of the important methodologies implemented across the world according to their objective are documented below.

Addis and Abebaw (2014) conducted a study in east Gojjam Zone of Ethiopia to assess the physical factors and chemical substances of soil which is important for the growth of garlic. Altogether 20 soil samples (5 sub samples each from 4 different sites) were randomly taken up to the depth of 20 cm and send to the laboratory for further analysis. Important factors such as pH, moisture, conductivity, organic carbon, organic matter (OM), cation exchange capacity (CEC), sodium (Na), Potassium (K), Calcium (Ca), and Magnesium (Mg) was measured in the laboratory. To see the variation in average value of these physical and chemical factors, statistical techniques such as; analysis of variance (ANOVA), correlation analysis, and other tools are used in SPSS software (Fig. 6.3).

With an objective to measure the physical factors and chemical substances present in the wetland soil, Manimegalal and Sukanya (2014) conducted a research in Muthannan Kulam wetland in Coimbatore of Tamilnadu, India. Black colored loamy soil containing sand was collected, allowed to dry in shade, and send for assessing basic soil properties after sieving. Soil parameters such as organic carbon, pH, electrical conductivity, nitrogen, phosphorus, and potassium were assessed by using common methodologies (Fig. 6.4).

Fig. 6.3 Soil sampling in the slope and rocky area of the forest in western Nepal

Fig. 6.4 Soil sampling in the grassland of western Nepal

With an objective to assess the variation in physical and chemical properties of soil in different depth and agro-climate, Kumar et al. (2012) conducted a study in Jharkhand of India. Different physical and chemical parameters such as; pH, electrical conductivity, soil organic carbon (SOC), calcium carbonate ($CaCO_3$), cation exchange capacity (CEC), and texture of soil was studied by using standard methods.

With an objective to assess the status of decay of litter, chemical composition, and its role in soil fertility, Das and Mondal (2016) conducted a research in Ramma reserve forest of West Bengal, India. For soil analysis, samples were taken from 5 different points of a plot up to the depth of 10 cm which were oven dried at 70 degree centigrade and passed through 2 mm sieve. Later, it was brought to the environmental chemistry laboratory of Burdwan University for analysis of soil pH, moisture, texture, bulk density, carbon content, available phosphorus, cation exchange capacity, and total nitrogen.

With an objective to assess the difference in chemistry of soil in shifting and Sloping Agricultural Land Technology (SALT), Biswas et al. (2010) conducted a study in agricultural area of Alutila, Khagrachari in Chittagong district, Bangladesh. Soil sampling was done up to the depths of 30 cm from 4 different sites and send for chemical analysis in laboratory.

Shaifullah et al. (2009) conducted a research to observe the impacts of coastal afforestation on physical and chemical parameters of soil in Hatiya coast of Noakhali area, Bangladesh. Detailed research was done from October 2006 to January 2008 in two different land areas at the depth of 0–10 cm, 10–30 cm, and 30–40 cm. Fourteen randomly mixed soil samples was taken from all three depth with the help of core augur from plantation and barren land finally making composite soil samples of 36 in each case. The physical and chemical parameters assessed from sampled soil were moisture, pH, texture, calcium, magnesium, salinity, available phosphorus, sodium, potassium, carbon content, soil density and total nitrogen.

With an aim to determine physical, chemical and pedogenetical properties of soil in relation to altitude Sevgi and Tecomen (2009) conducted a survey in Kazdagi upland black pine forest. Overall, 159 soil samples were collected from 37 soil profiles in terms of horizons. Relation of elevation and soil pH, total nitrogen, soil organic carbon and pedogenesis properties were explored following regular methodologies.

With an objective to assess the effect of elevation and land use on physiochemical parameter of acidic soil, Kidanemariam et al. (2012) conducted a study in Tsegede Highlands, Northern Ethiopia. Thirty six composite soil samples were collected from the surface layer (0–30 cm depth) of cultivated, grazing and forest land. Altitude of the sampling sites ranged from 2332 to 2965 m. Soil texture, available phosphorous, soil organic matter, total nitrogen, soil pH, and bulk density was measured using standard methods.

With an objective to explore the relative influence of soil chemistry (including soil pH, soil organic matter, total nitrogen, available phosphorus, and available potassium) and topography (including elevation, slope, aspect, and wetness index) on the availability of micronutrients (iron, manganese, copper, zinc and boron), Zhu et al. (2016) conducted a research using structural equation modeling (SEM) at the watershed scale. Soil pH, soil micronutrients, organic matter, available phosphorous, total nitrogen, available potassium, and topographic factors were measured at 523 sampling points of Fanshi County on the Chinese Loess Plateau. Geostatistical method was used to understand the distribution of soil micronutrient.

With an objective to assess the impact of altitude on physical and chemical parameters of soil, Saeed et al. (2014) conducted a research in Sra Ghurgai (Takatu mountain range) Quetta, Balochistan. Ten soil samples (0–30 cm depth) were collected from three locations in mountain range at 1660–2133 meters above sea level. Soil texture, pH, soil organic carbon, calcium carbonate, zinc, iron, copper and manganese were determined using usual methods. Also statistical methods such as, analysis of variance, correlation and regression analysis, was also carried out in statistical package for social survey 20 between different soil physical and chemical parameters in different altitudinal range.

Soil quality status was surveyed by Liao et al. (2015) on different land use types and cultivated land in Shiqu Country, China. Soil samples of cultivated land (0–20 cm depth), grassland and forest land (20–40 cm depth) were collected using auger. Soil samples were air dried and passed in 2 mm sieve for physical and chemical properties analysis. Soil properties were evaluated including soil pH, soil calcium carbonate, soil organic matter, total nitrogen, available phosphorus, total potassium, available nitrogen, and available potassium using standard methods. Also, Soil Quality Index (SQI) was measured of various land use type after determining these physical and chemical parameters.

The effects of land use on soil properties was observed by Gol (2009) at Dagdami river catchment in Turkey. Altitudinal range of the study area lies between 1100 and 1350 m above the sea level. Soil samples (0–5 and 5–15 cm depth) were collected from various land uses types at two aspects. Sample of soil was collected from upper, middle and lower slope position covering 24 disturbed and undisturbed soils. Steel core sampler of 100–400 cm^3 volumes were used to collect soil from undisturbed land. Statistical package for social survey was used to calculate analysis of variance and other statistical parameters.

6.5 Methods of Soil Quality Assessment in Nepalese Context

Nepal is a least developed country situated in South Asia encompassed by China from north and India from other three directions from a longitude of 80°04′–88°12′ E and latitude of 26°22′–30°27′ N. The area of Nepal is 147,181 km^2 falling in a length of about 800 km east-west and width of 144–240 km north-south having elevation from 60 to 8848 m (Paudyal 2002). There are various guidelines, manuals and techniques followed for assessment of soil quality and soil fertility. The main parameters and the procedure used for laboratory analysis in Soil Division, Nepal Agricultural Research Council is given below in Table 6.1.

In the context of Nepal, a composite soil rating method using a weighted ranking procedure can be prepared considering production and erosion chances with the help of data of soil texture, organic matter, pH and other nutrients. But this rating needs to be verified by using adequate data from different ecological zones. There are very limited studies focusing on soil quality status in the context of Nepal.

Table 6.1 Physiochemical parameters of soil and their methods used in Nepal

SN	Parameters	Methods
1	Soil texture	Hydrometer
2	Soil color	Munsell-color chart
3	Soil structure	Field-feel
4	Soil pH	Potentiometric 1:2
5	Soil organic matter	Walkely and black method
6	Total nitrogen	Kjeldahl method
7	Available phosphorus	Olsen method
8	Extractable potassium	Ammonium acetate method
9	Extractable calcium	EDTA titration method
10	Extractable magnesium	EDTA titration method
11	Available Sulphur	Turbidimetric method
12	Available boron	Hot water method
13	Available Iron	DTPA method
14	Available zinc	DTPA method
15	Available manganese	DTPA method
16	Available copper	DTPA method

Source: Adapted and modified from Khadka et al. (2017)

Agricultural research centers provide information of pH, carbon content, total nitrogen, P_2O_5 and K_2O of many thousands soil samples (Bajracharya et al. 2007).

With an objective to determine quality of soil in agricultural land, Khadka et al. (2017) conducted a study in regional agricultural research station in Tarahara of Sunsari district. Eighty one samples of soil in a surface of up to 20 cm depth were collected and physiochemical parameters of soil were measured.

With an aim to observe the physical and chemical factors affecting the fertility of forest soil, K C et al. (2013) conducted a study in one of the community forest of Syangja district of Nepal. Out of 40 samples, 9 samples were sent for detail laboratory analysis by using stratified random sampling method. Available standard method of soil analysis in laboratory of Nepal was used for assessing pH, organic matter, total nitrogen, available phosphorus, and available potassium.

Assessment of soil quality was performed by Kalu et al. (2015) on different land use system of Panchase area of western Nepal. Sixty soil samples (0–15 cm depth) from khet, bari, grassland, community forest and protected forest were collected to measure soil quality and nutrient reserves. Calculating the difference between wet and oven dried core soil sample, soil moisture was determined. Common methodologies were followed in the context of Nepal from Soil Division, NARC to measure nitrogen content, carbon content, available phosphorous, available potassium and soil texture. Soil management assessment framework was applied to measure soil quality index.

With an objective to assess the soil quality in different land use, Tiwari et al. (2006) conducted a study in Pokhre Khola watershed of the Middle Mountains in Nepal. Soil samples were collected by using transects method between 400 and 800 m. Altogether 24 soil profiles were sampled covering various land use (forest, bari and khet land). Common methodologies used in Nepal by Soil Division, NARC

Fig. 6.5 Consultation with local farmers during semi structured survey

were applied to determine soil texture, bulk density, carbon content, total nitrogen, available phosphorus, exchangeable sodium (Na) and cation exchange capacity. On the basis of these measured parameters, soil quality index of different land use was determined. Additionally, farmers were consulted for semi-structured survey (178 households) to identify their perception on soil quality and fertility management (Fig. 6.5).

With an objective to observe the role of Sloping Agricultural Land Technology in reducing runoff and soil loss, and enhancing soil fertility and maize production in slope, Lamichhane (2013) conducted a study in hilly region of Lalitpur district in central Nepal. The research was initiated in 1995 and soil sampling was done for 1 year. Physiochemical parameters of soil such as, organic matter, nitrogen, available phosphorus, available potassium, pH, soil texture, moisture content and water holding capacity was measured. Statistical tools, such as one way and two way ANOVA, Student–Newman–Keuls multiple range tests and non-parametric Kruskal–Wallis test was applied for analysis of collected data.

With an objective to assess the improvement of soil quality from agroforestry technique, Augustine et al. (2007) conducted a study in two mountainous village of south eastern part of Guatemala. Paired plots were selected in 2003 in three different places in a maize field (Site 1 and 2) and pasture (Site 3) which was used for agroforestry in 2000. To act as a control, there was land without agroforestry near it. After 3 year of plantation, 4 samples of soil were taken up to the depth of 20 cm categorized as upper part, middle up, middle bottom, and bottom. Soil parameters such as, total carbon and nitrogen, available phosphorus, iron, aluminum, texture, water-holding capacity was measured (Fig. 6.6).

Fig. 6.6 Agroforestry practice (*Zingiber officinale*) in the slope

With an objective to observe the impact of aspect of slope on biological, chemical and physical parameters of soil in varieties of land use, Begum et al. (2010) conducted a study in mid hill region of Makwanpur district in central Nepal. Forest land (community forest and government forest), shrub land or grazing land, agricultural land (slope terrace and low-lying paddy terrace farming) and sparse residential area were taken under consideration under different land uses. For sampling in northern and southern aspects, agricultural land and forest land, were taken under consideration while for statistical analysis, 4 replicate plots were taken in each sampling site. Forest land was considered as a control as it is less affected by human and has chances of high animal diversity and abundance than the farming land. Using simple random sampling method, sample of soil was taken in August 2008 with homogeneous area in term of slope and plant cover. Collected soil sample was dried in air and passed through 2-mm sieve for analyzing grain size, soil pH, carbon content, temperature, moisture, bulk density and fauna. Variation in these soil parameters according to land use and slope aspect was analyzed by using two-way ANOVA, correlation analysis and other statistical tools (Fig. 6.7).

With an aim to assess the impact of agroforestry practice to the soil quality, soil conservation and land use resilience, Schwab et al. (2015) conducted a research in Kolpu Khola basin of Nuwakot district in central mid-hill of Nepal. Random sampling method was used to find eight terrace field in each agricultural system making a total of 24 terraces. Four sample of soil was taken compositely (2 from plough layer and 2 from terrace risers. Collected soil sample was dried in air and passed through 2-mm sieve for analyzing conductivity, soil pH, total carbon, total nitrogen, phosphorus, cation exchange capacity, base saturation and grain size by using standard techniques. Statistical tools such as ANOVA, H-test, pgirmess, multcomp, agricolae and package gplots in R-software were used for detailed analysis.

Fig. 6.7 Assessment of flora and fauna in agricultural soil

Fig. 6.8 Laboratory analysis of soil quality

6.6 Status of Soil Quality in Global Context

From the above studies conducted in global scale by using various methodologies, quality of soil is observed as follows:

Survey conducted at black *Pinus* forest of Kazdagi Mountain showed that with the increase in altitude, total nitrogen and soil organic carbon values decreased at A horizon, and pH decreased at Bw horizons. Researcher concludes that effect of elevation is clearly visible in uppermost soil horizon (Sevgi and Tecomen 2009) (Fig. 6.8).

Addis and Abebaw (2014) observed that moisture content was varying significantly in different sites with highest in Bichena site. Soil pH was varying significantly from pH of 6.53 in Dejen area to 7.64 in Debre Werk area. Electrical conductivity was also varying significantly from 0.09 to 0.34 mS/cm in Dejen soil showing it as non-saline. Organic carbon was varying from 1.25% to 3.44% while organic matter was in higher value varying from 2.16% to 5.93%. Cation exchange capacity was varying from 30.75 in Debre Markos to 41.83 in Dejen area. Sodium ion was varying from 845 mg/kg in Dejen soil to 1014 mg/kg in Debre Werk. Potassium ion was varying from 1980 mg/kg in Debre Markos to 6065 mg/kg in Debre Werk. Calcium ion was varying from 952 mg/kg in Dejen soil to 2118 mg/kg in Bichena soil. Magnesium ion was varying from 1751 mg/kg in Dejen soil to 4288 mg/kg in Bichena soil.

Manimegalal and Sukanya (2014) observed neutral pH of 7.45 in Muthannan Kulam wetland soil but the value ranges from 7.25 to 8.71 in all other locations. Electrical conductivity was observed to be 1.43 dS/m in wetland but the value ranges from 1.14 to 5.26 dS/m. There was higher value of nitrogen (188 kg/ha), potassium (1266 kg/ha) and phosphorus (29 kg/ha).

Kumar et al. (2012) observed that pH value was increasing with increasing depth of soil in different aspects of soil showing collection of base in deep layers. Electrical conductivity was changing with depth but there was less variation in surface of the soil due to changing slope, permeability, dilution and leaching. Soil organic carbon was decreasing with increasing depth of soil due to more decay of living matter near the surface of the soil. Calcium carbonate ($CaCO_3$) was also increasing with increase in depth due to transfer of these chemicals deep inside the soil. Value of cation exchange capacity was higher in lower depth due to higher amount of clay and lower amount of soil organic carbon in lower depth.

Das and Mondal (2016) observed that the transfer of nitrogen, potassium and phosphorus by litter of different species was different. The transfer of nitrogen to the soil by *Tectona grandis* (about 153 kg/ha/year) was higher than that of *Shorea robusta* (about 142 kg/ha/year). Supply of phosphorus to the soil by *Tectona grandis* (about 13 kg/ha/year) was higher than that of *Shorea robusta* (about 5 kg/ha/year) but the potassium transfer by *Shorea robusta* (about 12 kg/ha/year) was higher than that of *Tectona grandis* (about 10 kg/ha/year). Fourth site had comparatively higher soil pH value than the first, second and third site for both the dry and moist soil.

Carbon content in hill farming system is higher than the 1-year fallow site after shifting cultivation. Degradation of soil from shifting cultivation had caused lowering of organic matter as compared to other farming systems. Carbon content in properly managed farming system, SALT was in balanced condition. Total nitrogen and carbon-nitrogen ratio was more in shifting cultivation with SALT as compared to the fallow site after shifting cultivation. With increasing depth of soil, phosphorus content was decreasing in most of the farming system except 8-year SALT abandoned area. But the available potassium content was following different trend as there was less K-content in 8-year abandoned SALT site as compared to other farming system due to regular shifting cultivation for long-term. Sodium content is also less in 1-year fallow site as compared to other farming system while calcium content is more in 3-year fallow site. Texture of soil is sandy in 1-year fallow land after shifting cultivation and SALT area of 8 year with shifting cultivation. Digging and clearing of land and destruction of forest for shifting cultivation increases soil erosion (Biswas et al. 2010).

Shaifullah et al. (2009) observed that planted site had more silt while barren land had more sand than other particles in the soil. Due to this, soil texture in planted site was loamy and the soil texture of barren char land was sandy. Barren land had low pH, carbon content, particle density, moisture, phosphorus, potassium and calcium but high salinity as compared to planted land and was increasing slightly while moving from inland to the sea side.

Augustine et al. (2007) observed that carbon content in soil was higher in agroforestry practice (4.3% C) as compared to farming without agroforestry practice (3.2% C). Total nitrogen content was also higher in agroforestry practice (0.16%) than the control plot without agroforestry (0.16%). There was no significant variation in baseline nutrient level of the plot in three sites without agroforestry practice. Clay, iron and aluminum content in Site 1 with Alfisol was 39–58%, 0.10–0.24% and 0.13–0.90%; Site 2 with Alfisol was 15–20%, 0.05–0.09% and 0.09%; and Site 3 with Vertisol was 36–61%, 0.20–0.32% and 0.18–0.20%, respectively. There was very less increase in carbon content in Site 2 which shows similar relationship with increased water holding capacity in agroforestry practice than without agroforestry practices. Overall, soil nutrients status (carbon and total nitrogen) and water holding capacity was better in agroforestry practices than that of non-agroforestry practice.

Result obtained by Kidanemariam et al. (2012) on altitudinal and land use impact on Tsegede Highlands, Northern Ethiopia showed significant ($P < 0.05$) correlation of soil bulk density, total nitrogen and organic matter with elevation. Soil organic matter declined in the lower elevation site (Indaslasie) by about 43–52% compared to other, two higher elevation sites (Cheguarcudo and Indamariam), respectively. Forest soils were less acidic than the cultivated and grazing lands. Organic matter content in the cultivated land was lower by about 25–35% compared to the grazing and forest soils, respectively. The study reflect that soil pH is not significantly affected by altitude but the type of land use affect significantly on not only soil pH but also other chemical properties like total nitrogen, available phosphorus and organic matter content. Soil organic matter decreases with the increase in the elevation above mean sea level. At lower elevation, bulk density was higher compared to higher elevation. Negative correlation exists between calcium carbonate and altitude. Calcium carbonate level decrease with the increase in elevation as the value of correlation coefficient is −0.990. Impact of elevation in soil pH is low as in lower elevation (1660 m), soil pH was 7.9 ± 0.15 while pH was recorded 8.0 ± 0.15 at higher altitude (2133 m). Soil electrical conductivity was high at 1660 m (210.7 ± 16.5) and low at 1804 m (120.7 ± 1.0) with the correlation coefficient of −0.095.

Results obtained from the study of altitudinal impact on soil physiochemical properties in Sra Ghurgia shows that with increase in altitude the percentage of organic matter in the soil is decreasing with the mean value 2.89 ± 0.48 at 1660 m and 1.82 ± 0.57 at 2133 m above mean sea level. Negative correlation exists between soil organic matter and the altitude. The value of correlation coefficient in between the organic matter content and elevation is −0.989 and between bulk density and elevation is −0.999. Composition of calcium carbonate was falling down with rise in altitude but soil pH was differing slightly. Composition of silt, available phosphorus, copper, manganese and zinc value was increasing with increase in altitude but electrical conductivity, sand and clay composition, available iron and potassium was decreasing with increase in altitude (Saeed et al. 2014).

The result obtained from the study of soil quality assessment in different land-use types in Shiqu County, China shows that the soil pH of forest and cultivated land are higher than that of grassland (5.5–6.5). Majority of soil in Shiqu County is neutral and slightly acidic. Soil organic matter content was determined in the order of grassland > forest land > cultivated land and SQI of various land use type is in the order of grassland (73.2%) > forest land (62.2%) > cultivated land (27.1%). Researchers conclude that addition of micronutrient in the soil is needed to improve soil fertility (Liao et al. 2015).

Research on impact of soil chemistry and topography on the micronutrient availability (iron, manganese, copper, zinc and boron) in cultivated land of Chinese Loess Plateau showed that topography affects directly on micronutrient availability (iron > zinc > manganese) except copper and boron. Soil chemistry directly affects micronutrient and were ranked as iron > boron > zinc > manganese > copper. In addition, soil chemistry is directly affected by topography (Zhu et al. 2016).

Result obtained by Gol (2009) shows that soil organic matter (SOM) and total nitrogen significantly vary with aspect and land use type. Study reflect significantly maximum values of saturated hydraulic conductivity in natural forest top soil (82.4 cm^3/ha on average) compared to grasslands soils (8.4 cm^3/ha) and hazelnut garden soils (11.5 cm^3/ha) and corn field soils (30.0 cm^3/ha). Water stable aggregates was determined greater in pasture and forest soils than in cultivated soils. Furthermore, soil organic carbon of forest soils is higher than other land use types.

6.7 Status of Soil Quality in Nepalese Context

Various studied were conducted on soil quality in different area of Nepal which shows results as explained below.

Lamichhane (2013) observed that SALT was able to manage soil and water from its bio-terraces in its demonstrated site. Soil nutrients and organic matter was enhanced by applying green manure, use of legume crops and fodder varieties, and input of external fertilizers. Use of fertilizers had impact on available potassium and phosphorus, total nitrogen content, carbon content, pH, soil moisture, water holding capacity, sand and clay. Also, farming practices had altered available potassium and phosphorus, carbon content, soil moisture, water holding capacity, and sand but had no significant impact on total nitrogen content, pH, silt and clay. SALT was appropriate in hills and mountains from ecological, social and economic point of view. It helps in maintaining ecosystem balance and increasing agricultural productivity in the hill terraces.

Schwab et al. (2015) observed that human developed terraces had weakly developed horizons with high dominance of sand. Soil pH was acidic ranging from 3.85 to 5.71 while electrical conductivity was ranging from very low value of 0.17 mS/

cm to higher value of 5.38 mS/cm. Carbon content was ranging from very low value of 0.004% to medium value of 3.43% while nitrogen content was ranging from lower value of 0.01% to higher value of 0.21%. Cation exchange capacity was ranging from very low value of 1.5 to 6.5 cmol, base saturation was ranging from 17.12% to 99.0% and phosphorus content was below 50 mg/kg.

Result obtained by Khadka et al. (2017) on soil fertility status of Sunsari, Nepal shows texture of soil with mean value of sand (30.32%), silt (48.92%), and clay (20.76%). Soil was found moderately acidic (mean pH 5.98) with medium status of organic matter (mean value 2.80%), nitrogen (mean 0.09%), available copper (mean 1.15 ppm), calcium (mean 1827.9 ppm), high status of P_2O_5 (mean 39.77 ppm), K_2O (mean 134.12 ppm), manganese (mean 18.15 ppm). Soil quality test in laboratory revealed low value of magnesium (mean 44.33 ppm), sulphur (mean 2.17 ppm), boron (mean 0.08 ppm), available zinc (mean 0.35 ppm), very low status of available zinc (mean 0.35 ppm) and very high status of available iron (mean 244.7 ppm).

K C et al. (2013) observed that pH in the forest soil was slightly acidic varying from pH of 5.59–7.18 in grassland. Soil organic matter was varying from 0.65% in grassland to 2.39% in the dense strata due to high decomposition of dry leaf litter. Total nitrogen was ranging from 0.09% to 0.12% while available phosphorus was ranging from 81.85 to 93.23kg/ha.

Carbon content was more in northern aspect as compared to southern aspect and was directly related with soil pH, soil moisture, bulk density, and animal diversity. There was neutral to slightly alkaline pH in southern aspect while it was slightly acidic in northern aspect. High moisture and carbon content, and different vegetation cover causes decrease in pH in northern aspect as compared to southern aspect. This results in increased abundance and diversity of animal in northern aspect than that of southern aspect. Also, moisture content is related to carbon, soil temperature, abundance, pH, and bulk density. Bulk density of forest area and farming sites was lower in northern aspect but it was insignificant due to the increase in carbon content, faunal diversity and moisture content in it. Temperature of soil was more on the southern aspect as compared to the northern aspect. Soil functions and agricultural sustainability depending on diversity of animal was lower on the southern aspect due to low soil moisture. Due to the destruction of soil habitat and higher exposure of agricultural land to tilling, crop growth, chemicals and pesticides, there was low species diversity on northern slope. But, in case of southern slope, animal diversity was higher in agricultural field than the forest. It was due to the presence of rocks and thin layered soil, change in slope, less moisture, smaller depth of soil and tree crown coverage, and degraded forest land (Begum et al. 2010).

By observing the information of soil parameters of regional agricultural centers of Nepal, more than 90% of soil sample had low to medium level of carbon content and total nitrogen. Acidic soil was observed in 55% of samples while majority of soil sample has low level of exchangeable potassium. Carbon content and total nitrogen was increasing in higher altitude and in northern aspect as a result of cold environment, high moisture and slow rate of decomposition. In the centre and west of Nepal, soil was loamy sand to clay loam based on soil profile (Bajracharya et al. 2007).

Results obtained by Kalu et al. (2015) on the study of soil quality of Panchase region reflects soil was sandy loam with significantly higher bulk density in pasture land followed by agriculture (khet and bari) and then after forest soil. Decomposition of litter in forest usually makes soil loose. Due to active rain in study area in all land use type pH of soil was found to be acidic (pH < 7). Bari and pasture land has higher pH value followed by protected forest, khet, and community forest. Pine tree was dominant species in community forest and hence soils of pine tree forest are acidic due to litter. In case of soil quality, soil quality index of protected forest (0.95) is the highest followed by community forest (0.91), pasture (0.88), khet (0.81), and bari (0.79). Soil quality index of protected land is high as it is less disturbed than other land use type.

Results obtained from the study of biophysical and socio-economic tools for assessing soil fertility: A case of western hills, Nepal by Tripathi and Jones (2010) shows that Soil pH, organic carbon, total N, available P and exchangeable K were affected by altitudes (P = <0.001). The highest pH (6.1) was recorded at <600 m altitude. Organic carbon, nitrogen, phosphorus, potassium values increased at higher altitude (Tables 6.2 and 6.3). Altitude did not affect the micronutrients (zinc, iron, manganese and copper) except boron (P = 0.05), which increased at higher altitudes (Tables 6.2 and 6.3).

Soil quality assessment in Pokhre Khole by Tiwari et al. (2006) showed that *Bari* land had higher pH, carbon, nitrogen, phosphorus and potassium than other land use

Table 6.2 Effect of altitudes on macro plant nutrients in the western hills

Altitudes	pH	OC(%)	Total N(%)	Available P(mg/Kg)	Ex. K(mg/Kg)
<600 m	6.05	1.07	0.15	30.2	0.40
600–1000 m	5.80	1.59	0.17	43.8	0.32
1000–1600 m	5.64	2.24	0.22	98.1	0.42
1600–2200 m	5.66	2.90	0.27	202.2	0.45
Mean	5.79	1.95	0.20	93.6	0.40
SEM	0.11	0.13	0.01	18.1	0.06
P value	0.001	<0.001	<0.001	<0.001	0.10

Source: Adapted and modified from Tripathi and Jones (2010)

Table 6.3 Effect of altitudes on micro plant nutrients in the western hills

Altitudes	Av. Zn(mg/Kg)	Av. Fe (mg/Kg)	Av. Mn(mg/Kg)	Av. Cu(mg/Kg)	Av. B (mg/Kg)
<600 m	0.91	174.0	46.3	1.29	0.50
600–1000 m	1.05	179.4	55.9	1.42	0.55
1000–1600 m	0.87	194.6	61.5	1.59	0.65
1600–2200 m	0.85	174.2	68.4	1.68	0.66
Mean	0.92	180.6	58.0	1.50	0.59
SEM	0.16	10.5	10.5	0.29	0.07
P value	0.56	0.10	0.30	0.56	<0.05

Source: Adapted and modified from Tripathi and Jones (2010) pattern. Researchers observed soil quality index of Bari (SQI = 0.59), forestland (SQI = 0.45) and khet (SQI = 0.23). This shows bari and forest land at risk and khet land at degraded condition. Literature on soil quality of land use reflects that nutrient level and soil organic carbon is higher in forest land than in cultivated land. The reason behind lower SOC in forest is due to elevation in biomass removal by local residents for domestic fodder and bedding resource.

6.8 Discussions and Conclusions

From the above studies, it is observed that researches are performed in varieties of soil type, land use and slope aspect in different part of Nepal and the whole world. Similar standard methods were applied for assessing physical, chemical and biological characteristics of soil. First of all, soil sample was taken by using standard soil sampling technique and passed through sieve for getting required volume and size of soil samples. Physical parameters such as soil texture, colour, grain size distribution, and water holding capacity were determined in the field and laboratory. Chemical parameters such as soil pH, conductivity, nitrogen, carbon, potassium, phosphorus, and other heavy metals were measured in the laboratory by applying standard procedure. Biological parameters such as floral and faunal diversity and abundance were also observed in the field and laboratory. After determination of these parameters, soil quality was assessed by using different indices and assessment methods.

In case of global context, moisture content, pH, electrical conductivity, organic matter, sodium, potassium, calcium, and magnesium was varying significantly in different sites of Gojjam Zone of Ethiopia (Addis and Abebaw 2014). Agroforestry practice in soil had better nutrient quality as compared to other farming practices in term of nitrogen, carbon and water holding capacity in mountainous village of south eastern part of Guatemala (Augustine et al. 2007).

There was variation in pH, electrical conductivity, nitrogen, potassium, and phosphorus in Muthannan Kulam wetland soil in Tamilnadu of India (Manimegalai and Sukanya 2014). Electrical conductivity, pH, soil organic carbon, calcium carbonate, and cation exchange capacity was changing with the change in depth in Jharkhand, India (Kumar et al. 2012). Nitrogen, potassium and phosphorus supply on soil by different plant species is slightly different in Ramma reserve forest of West Bengal, India (Das and Mondal 2016).

Shifting cultivation, sloping agricultural land practices and abandoned sites had different level of nutrient content and different level of erosion due to disturbance in soil by digging and clearing of land in Alutila, Khagrachari of Chittagong district, Bangladesh (Biswas et al. 2010). Planted site had better nutrient quality as compared to barren site and they had different level of soil texture, pH, soil organic carbon, particle density, soil moisture, phosphorus, potassium, calcium and salinity in Hatiya coast of Noakhali area, Bangladesh (Shaifullah et al. 2009).

In the Nepalese context, soil in agroforestry system had better quality and condition as compared to conventionl system in term of pH, conductivity, carbon, cation exchange capacity, base saturation and phosphorus in Kolpu Khola basin of Nuwakot district in central mid-hill of Nepal (Schwab et al. 2015). Sloping agricultural land technology had better nutrient content due to the use of green manure, nitrogen absorbing fodder varieties and input of external fertilizers in Godawari area of Lalitpur district, Nepal (Lamichhane 2013). Aspect of soil was also affecting the soil quality as soil carbon, pH, soil moisture, and animal diversity was better in northern aspect bulk density. Soil organic carbon was higher in high altitude and in northern aspect as a result of cold environment, high moisture and slow rate of decomposition in different region of Nepal (Bajracharya et al. 2007).

Carbon content was more in northern aspect as compared to southern aspect and was directly related with soil pH, soil moisture, bulk density, and animal diversity. There was neutral to slightly alkaline pH in southern aspect while it was slightly acidic in northern aspect. High moisture and carbon content, and different vegetation cover causes decrease in pH in northern aspect as compared to southern aspect. This results in increased abundance and diversity of animal in northern aspect than that of southern aspect in mid hills of central Nepal (Begum et al. 2010). Soil was sandy loam with high bulk density in pasture land followed by cultivated land and forest soil due to high decomposition of litter in forest. Soil quality index was higher in protected forest, followed by community forest, pasture, khet and bari (Kalu et al. 2015).

Overall, different soil type in different region had variation in soil quality. Properly managed agricultural system had higher soil quality index and soil fertility than as compared to traditional agricultural system. Also, forest area and grassland with fewer disturbances had better soil quality than as compared to disturbed areas. It is better to use appropriate agricultural technology to prevent soil loss and maintain soil quality in the slopes. As the slope aspect and altitude had caused variation in soil quality, it is necessary to consider these parameters for getting higher agricultural output, decreasing loss of soil, increasing income, and maintaining the standard of living of the people. Regular assessment of physical, chemical, and biological parameters of the soil and monitoring of soil quality index in regular interval of time is important for sustainable management of soil productivity.

References

Addis W, Abebaw A (2014) Analysis of selected physicochemical parameters of soils used for cultivation of garlic (*Allium sativum*). Sci Technol Arts Res J 3:29–35

Anup KC, Kalu S (2015) Soil pollution status and its remediation in Nepal. In: Hakeem KR, Sabir M, Ozturk M, Mermut AR (eds) Soil remediation and plants, prospects and challenges. Elsevier Academic Press, London

Anup KC, Bhandari G, Wagle SP, Banjade Y (2013) Status of soil fertility in a community forest of Nepal. Int J Environ 1:56–67

Augustine CMJ, Vogt KA, Harrison RB, Hunsaker HM (2007) Nitrogen-fixing trees in small-scale agriculture of mountainous Southeast Guatemala. J Sustain For 23:61–80

Bajracharya RM, Sitaula BK, Sharma S, Jeng A (2007) Soil quality in the Nepalese context – An analytical review. Int J Ecol Environ Sci 33:143–158

Begum F, Bajracharya RM, Sharma S, Sitaula BK (2010) Influence of slope aspect on soil physico-chemical and biological properties in the mid hills of Central Nepal. Int J Sustain Dev World Ecol 17:438–443

Biswas S, Swanson ME, Shoaib JUM, Haque SMSS (2010) Soil chemical properties under modern and traditional farming systems at Khagrachari, Chittagong hill tracts, Bangladesh. J For Res 21:451–456

Das C, Mondal NK (2016) Litterfall, decomposition and nutrient release of *Shorea robusta* and *Tectona grandis* in a sub-tropical forest of West Bengal, Eastern India. J For Res 27:1055–1065

Gol C (2009) The effects of land use change on soil properties and organic carbon at Dagdami river catchment in Turkey. J Environ Biol 30:825–830

Griffiths RP, Madritch MD, Swanson AK (2009) The effects of topography on forest soil characteristics in the Oregon Cascade Mountains (USA): implications for the effects of climate change on soil properties. For Ecol Manag 257:1–7

Kalu S, Koirala M, Khadka UR, Anup K (2015) Soil quality assessment for different land use in the Panchase area of western Nepal. Int J Environ Prot 5:38–43

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1995) Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Sci Soc America J 61:4–10

Khadka D, Lamichhane S, Shrestha SR, Pant BB (2017) Evaluation of soil fertility status of regional agricultural Research Station, Tarahara, Sunsari, Nepal. Eur J Soil Sci 6:295

Kidanemariam A, Gebrekidan H, Mamo T, Kibret K (2012) Impact of altitude and land use type on some physical and chemical properties of acidic soils in Tsegede highlands, Northern Ethiopia. Open J Soil Sci 2:223

Kumar R, Rawat KS, Yadav B (2012) Vertical distribution of physico-chemical properties under different topo-sequence in soils of Jharkhand. J Agril Phys 12:63–69

Lamichhane K (2013) Effectiveness of sloping agricultural land technology on soil fertility status of mid-hills in Nepal. J For Res 24:767–775

Liao W, Tang D, Wang X, Cheng X (2015) Soil quality status of different land use types in Shiqu country, China. International Symposium on Energy Science and Chemical Engineering [Online].

Manimegalai K, Sukanya S (2014) Assessment of physico-chemical parameters of soil of Muthannan Kulam wetland, Coimbatore, Tamilnadu, India. Int J Appl Sci Biotechnol 2:302–304

Paudyal K (2002) Geology for civil engineers. Oxford International Publication, Oxford

Saeed S, Barozai MYK, Ahmad A, Shah SH (2014) Impact of altitude on soil physical and chemical properties in Sra Ghurgai (Takatu mountain range) Quetta, Balochistan. Int J Sci Engin Res 5:730–735

Schwab N, Schickhoff U, Fischer E (2015) Transition to agroforestry significantly improves soil quality: a case study in the central mid-hills of Nepal. Agric Ecosyst Env 205:57–69

Sevgi O, Tecomen HB (2009) Physical, chemical and pedogenetical properties of soils in relation with altitude at Kazdagi upland black pine forest. J Env Biol 30:349–354

Shaifullah KM, Sirajul Haque SM, Sujauddin M, Karmakar S (2009) Coastal afforestation effects on soil properties at Hatiya in Bangladesh. J For Res 20:243–248

Tiwari KR, Sitaula BK, Borresen T, Bajracharya RM (2006) An assessment of soil quality in Pokhare Khola watershed of the middle mountains in Nepal. J Food Agri Env 4:276

Tripathi BP, Jones JE (2010) Biophysical and socio-economic tools for assessing soil fertility: a case of western hills, Nepal. Agron J Nepal 1:1–9

Zhu H, Zhao Y, Nan F, Duan Y, Bi R (2016) Relative influence of soil chemistry and topography on soil available micronutrients by structural equation modeling. J Soil Sci Plant Nutr 16:1038–1051

Soil Fertility Improvement by Symbiotic Rhizobia for Sustainable Agriculture

7

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Abstract

Soil is living medium and it acts as a precarious reserve in agriculture and food production. To enhance crop yields for ever-increasing human population, chemical fertilizers are being applied in the soil. But, the haphazard usage of fertilizers, predominantly nitrogenous and phosphorus, headed to considerable contamination of soil, air and water. Moreover, unwarranted consumption of these agrochemicals also cause lethal effects on soil microorganisms and disturbs the soil fertility. Due to current public apprehensions about the side effects of these agrochemicals, understanding plant and rhizospheric microbial interactions is gaining momentum. It is considered to be important to effectively manage level of nitrogen in soil through biological nitrogen fixation (BNF) to maintain agricultural sustainability. The fixed N is directly taken up in the plants and is less vulnerable to volatilization, denitrification and leaching. Thus, mutualistic symbiosis amongst legume plant and nodulating rhizobia plays a key role in ecological environments. Legume-rhizobia symbioses provide approximately 45% of N used in agriculture and contributions of BNF from the symbiotic association accounts for at least 70 million metric tons per year into terrestrial ecosystems. In agricultural systems, about 80% of BNF contributed by symbiotic association made between leguminous plants and species of *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Azorhizobium*, *Mesorhizobium* and *Allorhizobium*. The populations of these root-nodule forming bacteria can be changed ecologically, agronomically, edaphically and genetically to increase legume production and soil productivity. Moreover, legume-rhizobia symbioses also provide non-polluting and economical ways to augment N_2-fixing potential under stress conditions. Scientists have identified numerous symbiotic systems

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tolerant in harsh situations of salinity, alkalinity, acidity, drought, toxic metals have been recognized and alteration in rhizobial population under stressed environments can be an indicator of soil fertility. Moreover, interactions among rhizobia, plant growth-promoting rhizobacteria (PGPR) and mycorrhiza as well show significant part in increasing soil fertility and crop yields. In this chapter, significance of biological nitrogen fixation in persistent food supply, influence of extreme environments on legume-rhizobia symbiosis as well as interaction of rhizobia with belowground microbial species are discussed. The eco-friendly approach to increase crop production and soil health by inoculation of symbiotic bacteria as biofertilizers is described for sustainable agriculture.

Keywords
Soil · Microbial population · Biological nitrogen fixation · Rhizobia · PGPR

7.1 Introduction

Legumes can be considered as key source of proteins in vegetarian diet in developing countries (Nedumaran et al. 2015). Therefore there is a need to improve the yield of legumes and to sustain soil fertility. Legumes utilized for human feed comprise of dry and green beans, broad beans, dry and green peas, chickpeas, lentils, soybeans, lupins, mung beans and peanuts. Nitrogen (N) and phosphorus (P) are major regulating nutrients for growth of leguminous plants. Replenishment of these nutrients to the legume crops is mostly done through application of inorganic nitrogenous and phosphate fertilizers to soil. Addition of nitrogenous fertilizers is the major external input for maximizing crop yield in agriculture. Inadequate usage of these chemical fertilizers has contaminated environment and causes various health hazards. Moreover, due to the low use efficiency of nitrogen fertilizers among plant nutrients and their continuous use leads to slow deterioration in soil health (Newbould 1989; Bockman 1997) and a decline in crop yield (Bohlool et al. 1992). Additional drawbacks of N-fertilizers include speeding up the depletion of non-renewable energy resources. Along with high usage of N fertilizers in developed countries, volatilization of N oxides (greenhouse gases) into environment and leaching of NO_3^- into ground water, is also a major threat for global N cycle.

Due to exponential growth of population, its demand of the day to implement new means of improving food production that are well-suited with sustainability and preservation of environmental quality (Sindhu and Dadarwal 1995b; Sharma et al. 2018a, b). Moreover, rates of nitrogenous and phosphatic fertilizers is continuously increasing in developing countries and these fertilizers are not only unaffordable or unavailable in many countries but also have other drawbacks. Therefore, it is actually critical task for farmers to add-on N and P fertilizers in soil to escape the nutrient insufficiencies. Viable agriculture consist of effective management of agricultural assets to fulfill shifting human requirements, while preserving or increasing environmental superiority and safeguarding natural assets. Thus sustainability deliberations requires substitutes to nitrogen fertilizer. Biological nitrogen fixation can be considered as substitute in farming practices as it uses capability of several nitrogen-fixing bacteria to transform atmospheric nitrogen into the plant usable, ammonia using the nitrogenase enzyme (Bohlool et al. 1992).

Legumes are grown approximately on 252 million hectares of land, leading to about 90 Tg of dinitrogen being fixed per year, with major contributors to overall N_2 fixation through legume–*Rhizobium* symbiosis (Smith and Giller 1992). The growth of grain legumes such as field pea (*Pisum sativum* L.), followed by the subsequent decomposition of N rich residues helps to replenish N removed by harvesting. This leads to savings of fertilizer N and brings about enrichment of soil N, which is available to subsequent crops (Jensen and Hauggaard-Nielsen 2003). By using nitrogen-fixing species of microorganisms in cropping systems dependency of agricultural crops on chemical nitrogenous fertilizers can be reduced. Moreover, biologically fixed nitrogen resides within soil organic matter in bounded form and hence it is considerably less vulnerable to chemical alterations as well as physical losses like volatilization and leaching. Considering adverse environmental effects of chemical fertilizers and growing prices, use of plant growth promoting rhizobacteria (PGPR) and rhizobia is valuable for sustainable agricultural system (Fernández et al. 2007; Shiri-Janagard et al. 2012; Uribe et al. 2012; Sindhu et al. 2018). A lot of information exists on the positive influence of *Rhizobium* and *Bradyrhizobium* on legumes in terms of biological nitrogen fixation (Werner 2005) and in cereal–legumes crop rotation systems. Moreover, coinoculation of symbiotic bacteria with PGPR is another approach which has been found to improve root and shoot weight, plant vigour, nitrogen fixation and grain production in legumes (Valverde et al. 2006; Yadegari et al. 2008; Verma et al. 2013; Sindhu et al. 2017).

This chapter describes diversity detected among different symbiotic bacteria and contribution of different rhizobia in increasing the growth and yield of legume crops as well as various biotechnological approaches undertaken for improving biological nitrogen fixation. The various limitations faced to improve crop productivity by inoculation with bacterial strains and opportunities of getting anticipated profits by confirming the establishment and survival of inoculated microbes in soil has also been discovered.

7.2 Role of Nitrogen Fixation by Bacteria in Cereal and Legume Crops

Majority of naturally augmented nitrogen in soils is from symbiotic or asymbiotic biological fixation carried out by microorganisms. As per an estimate annually roughly 100 Tg N, is needed for production of world's grain and oilseed crops (David and Ian 2000). Legume crops possess remarkable potential for biological nitrogen fixation in soil ecosystems (Brockwell et al. 1995). There exist roughly 700 genera and around 13,000 species of legumes and from such a large variety of legumes only a small part was studied for nodulation and nitrogen fixation efficiency (Sprent and Sprent 1990). Assessments showed that symbiotic association of

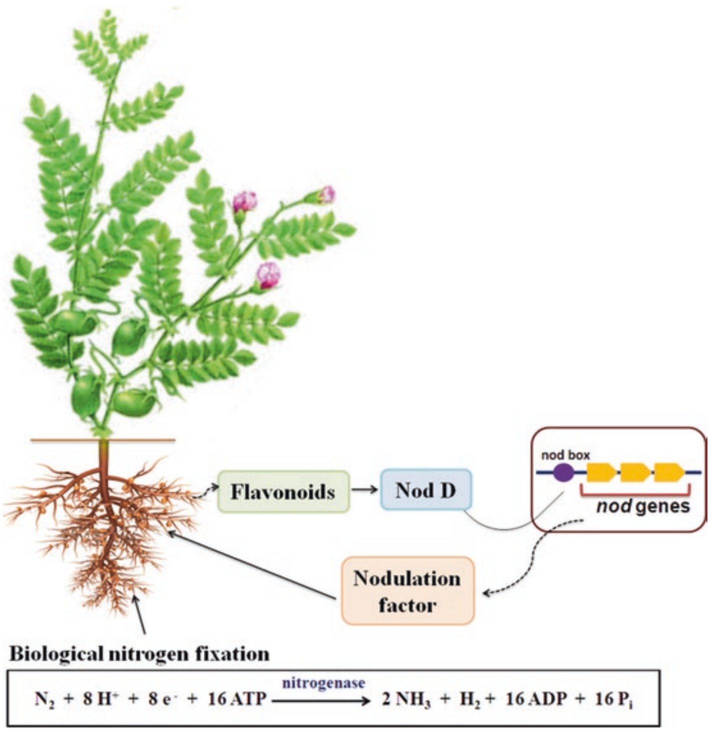

Fig. 7.1 **Nodulation and nitrogen fixation is illustrated in chickpea plant**. The coordinated and controlled expression of nodulation genes of rhizobia in response to plant-released flavonoids synthesize the nodulation factor that leads to nodule organogenesis. The differentiated bacteroids in the nodules utilize nitrogenase enzyme to convert atmospheric nitrogen into ammonia.

Rhizobium with approximately 100 agriculturally significant legumes, add roughly half the annual amount of BNF inflowing soil ecosystems (Tate 1995). Legume symbioses add approximately 70 million metric tonnes of N per yea, from which half is derived from cool and warm temperature zones and rest is resulting from tropics (Brockwell et al. 1995; Freiberg et al. 1997).

The success and sustainability of many food crops, forage and green manure legumes is mainly obligated to their symbiotic association with particular nitrogen-fixing rhizobia (Menna et al. 2006). A peculiar characteristic that distinguishes rhizobia from other nitrogen-fixing bacteria is their unique ability to elicit the development of a specialized nodule to form a symbiotic association with their legume host (Lindstrom et al. 2006) (Fig. 7.1). This association converts atmospheric inert N_2 to a renewable source of fixed N for agriculture with expected values falling in range of 57–600 kg of N ha^{-1} $year^{-1}$ (Zahran 1999; Ramankutty et al. 2018). In contrast to application of inorganic N-fertilizers. N input through the process of BNF not only maintains the soil's N reserves but can also conserve natural resources. In that way, BNF plays significant role in nourishing throughput of soils.

Table 7.1 Average biological nitrogen fixation by various plant microbe associations

Nitrogen-fixing system	Microorganisms/plants	Rate of nitrogen fixation (kg ha^{-1} $year^{-1}$)
Free-living microorganisms	Cyanobacteria (blue-green algae)	7−80
	Azotobacter	0.3−15
	Clostridium pasteurianum	0.1−0.5
Grass-bacteria associative symbioses	*Azospirillum*	15−36
	Acetobacter diazotrophicus	150–200
Plant-cyanobacterial associations	*Gunnera*	12−21
	Azolla-Anabaena	45−450
	Lichens	39−84
Rhizobium–legume symbioses	Soybeans (*Glycine max* L. Merr.)	57–94
	Cowpea (*Vigna*, *Phaseolus* and others)	84
	Clover (*Trifolium pratense* L.)	104–160
	Alfalfa (*Medicago sativa* L.)	128–600
	Lupines (*Lupinus* sp.)	150–169
Nodulated non-legumes	*Alnus* (alders, e.g. red and black alders)	40–300
	Hippophae (sea buckthorn)	2–179
	Coriaria ('tutu' in New Zealand)	60–150
	Casuarina (Australian pine)	58

Adapted and modified from Stevenson (1982)

Some bacteria and cyanobacteria have developed capacity to convert atmospheric nitrogen in to ammonia using nitrogenase enzyme and supply this important nutrient into agricultural soils. BNF take place in the free-living state, in association with or in symbiosis with plants (Table 7.1). Inoculation of various strains of diazotrophic bacteria carried out to increase amount of nitrogen as nutrients to several leguminous and non-leguminous crops. Vast areas of aerable land in Australia, India, Russia and United Kingdom inoculated with non-symbiotic N_2-fixing bacteria such as *Azotobacter*, *Azospirillum*, *Bacillus* and *Klebsiella* spp. with the goal of improving plant yield (Lynch 1983; Sloger et al. 1992; Di Benedetto et al. 2017). In symbiotic system, *Rhizobium* species have been effectively utilized globally as a bioinoculant leading to effective establishment of N_2-fixing symbiosis with leguminous crops (Eaglesham 1989; Thies et al. 1991; Dahale et al. 2016). Other N_2-fixing symbionts, such as *Frankia* spp. have also been successfully introduced into soil (Sougoufara et al. 1989; Clawson et al. 1998).

Another approach to improve nitrogen budget of crops is to inoculate symbiotic bacteria with PGPR in leguminous crops to improve root and shoot weight, plant vigour, nitrogen fixation and grain yield in several legumes (Valverde et al. 2006; Yadegari et al. 2008; Verma et al. 2013; Sindhu et al. 2017). By modulating balance of deleterious vis a vis beneficial microbial activities in rhizosphere, PGPR are known to encourage plant growth directly by producing phytohormones, by improving nutrient accessibility and acquisition or eliciting plant defense mechanisms, which in turn, leads to increased nutrient acquisition and growth (Sindhu et al. 2014, 2016) or induce systemic resistance against harmful microorganisms (Liu et al. 1995a, b). Therefore, synergistic consortia of microbes having various metabolic abilities (N_2 fixation, P mobilization, synthesis of plant growth hormones and bioactive molecules) can definitely perform better than single inoculations. However, type of inoculums, method of inoculation and agricultural practices can influence the effect of the inoculation. The effect of multiple inoculants with symbiotic N_2 fixing rhizobia, asymbiotic free-living N_2 fixing bacteria and phosphate solubilising bacteria or cyanobacteria found to stimulate plant biomass in different legumes.

Symbiotic association between leguminous plants and *Rhizobium* is the best comprehensively studied nitrogen-fixing system. This symbiotic association fixes around 70–80% of the total BNF per year (Ishizuka 1992). Nitrogen fixation capacity of symbiotic rhizobia range from 57 to 600 kg N ha^{-1} yearly (Elkan 1992). Among legumes, soybean is leading crop legume, comprising of 50% of the global crop legume area and soybean was reported to fix 16.4 million tones N annually, representing 77% of the nitrogen fixed by the crop legumes (Herridge et al. 2008). Increase in legume production are usually equal to those estimated from inoculation of 30–80 kg of fertilizer-N ha^{-1}. Inputs of fixed N for alfalfa, red clover, pea, soybean, cowpea and vetch are expected to be nearly 23–335 kg of N ha^{-1} $year^{-1}$ (Tate 1995; Wani et al. 1995). Thus, efficiency of various legume species and their microsymbionts has been found variable (Table 7.1). In general, faba bean (*Vicia faba*) and pigeon pea (*Cajanus cajan*) have been found to be very efficient; soybean (*Glycine max*), ground nut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) to be average; and common bean (*Phaseolus vulgaris*) and pea (*Pisum sativum*) less efficient for nitrogen fixation (Hardarson 1993; Pinto et al. 2007). The *Azolla-Anabaena* symbiotic system proved to add 45–450 kg N ha^{-1} and *Frankia*-actinorhizal symbiosis deliver 2–362 kg N ha^{-1} (Elkan 1992).

Sindhu and Dadarwal (1992) carried out experiment to evaluate comparative efficiency of nitrogen fixed by *Rhizobium* strains in chickpea using non-nodulating genotype PM233 obtained from wild type nodulating genotype ICC640. Due to nitrogen fixation by *Rhizobium* strains Ca534 and Ca219 in nodulating genotype ICC640, significant increase in plant dry weight was obtained over application of 80 kg N ha^{-1} through urea in non-nodulating mutant PM233. The results reveal the fact that effective symbiosis between rhizobia and chickpea can supplement more than 80 kg N ha^{-1}. Profits of nitrogen fixation in legume crops to succeeding cereal crops are considerable and carry on for several years as a result of gradually slow mineralization. In green manuring crops greater amount of benefits of rhizobia and plant symbiosis were observed and about 532 kg N could be assimilated by 60 days with nitrogen N accumulation rate of 10.8 kg N ha^{-1} day^{-1} (Peoples and Herridge 1990).

Fixed nitrogen is also made accessible to an intercrop or succeeding crop. Generally more than 50% of the crops grown in Africa, India and Latin America are

Table 7.2 Growth promoting substances synthesized by rhizobia involved in stimulating plant growth

Rhizobia	Growth promoting substances synthesized	References
Rhizobium and *Bradyrhizobium*	Siderophores, P-solubilization, IAA, HCN	Abd-Alla (1994a, b), Antoun et al. (1998), Duhan et al. (1998), Khan et al. (2002), Deshwal et al. (2003a) and Tank and Saraf (2010)
Rhizobium sp.	Growth hormones, IAA, siderophores, HCN, ammonia, exopolysaccharides	Ahemad and Khan (2009a, 2012a), Joseph et al. (2007), Wani et al. (2007b) and Zafar-ul-Hye et al. (2013)
R. phaseoli	IAA	Arora et al. (2001)
R. ciceri	Siderophores	Berraho et al. (1997)
R. leguminosarum	Cytokinin	Zahir et al. (2010)
M. ciceri	IAA, siderophores	Wani et al. (2007c)
Mesorhizobium sp.	IAA, siderophores, HCN, ammonia, exopolysaccharides, antifungal activity	Ahemad and Khan (2009b, 2012c), Ahmad et al. (2008), Khan et al. (2002) and Wani et al. (2008a)
B. japonicum	IAA, siderophores	Wittenberg et al. (1996) and Shaharoona et al. (2006)
Bradyrhizobium sp.	IAA, HCN, ammonia, siderophores, exopolysaccharides	Khan et al. (2002), Wani et al. (2007a) and Ahemad and Khan (2011, 2012b)
R. meliloti	Siderophores	Prabha et al. (2013)

either intercropped or rotated with nitrogen-fixing crops (Fujiata et al. 1992). Hence biological nitrogen fixation assists as an efficient way to reduce reliance on chemical fertilizers by supplying nitrogen to symbiont as well as builds up soil nitrogen for subsequent crops. However, numerous soil environmental causes viz. temperature, moisture, acidity, available nitrogen, phosphorus, calcium and molybdenum content affect nitrogen fixation (Somasegaran and Bohlool 1990; Zhang et al. 1996). Application of efficient strain of rhizobia on legumes generally resulted in substantial rise in production of several legume crops (Eaglesham 1989; Thies et al. 1991) (Table 7.2). Although, numerous reports also showed unpredictability in attaining the yield increases ensuing application of rhizobial strains (Miller and May 1991).

7.3 Rhizobial Diversity

Phylogenetically rhizobia are very different, demonstrating numerous lineages. Rhizobia presently comprise of 12 genera and beyond 113 species of α- and β-proteobacteria (Sawada et al. 2003). Rhizobia are distributed in the following genera: *Aminobacter* (1), *Azorhizobium* (3), *Bradyrhizobium* (15), *Devosia* (1), *Mesorhizobium* (29), *Methylobacterium* (1), *Microvirga* (3), *Ochrobactrum* (2), *Phylobacterium* (1), *Rhizobium* (43), *Sinorhizobium/Ensifer* (13) and *Shinella* (1). Additionally, there are 9 species of β-rhizobia, namely *Burkholderia* (6), *Cupriavidus* (2) and *Herbaspirillum* (1). Many new species of rhizobia are described each year and even strains from non-typical rhizobia genera are included to list of rhizobia, as strains from the *Burkholderia* genus (Chen et al. 2003, 2008). In general, rhizobia are heterotrophic and aerobic non-sporulated rods, however, there are *Bradyrhizobium* strains having ability of anaerobic growth (Polcyn and Luciński 2003), photosynthetic bradyrhizobia (So et al. 1994) and methylotrophic *Methylobacterium* strains (Sy et al. 2001). The complete genomic sequence of photosynthetic bradyrhizobia able to induce both root and stem nodules revealed that these strains lack the canonical *nod*ABC genes required for Nod factor synthesis (Giraud et al. 2007).

Crook (2013) isolated *Rhizobium* sp. IRBG74 and *A. caulinodans* from *Sesbania aculeata* and *Sesbania rostrata* and capable of colonizing rice roots. Endophytic strain of *Rhizobium* sp. IRBG74 was also isolated from *Sesbania cannabina*, but it lacks *nif*V gene required for nitrogen fixation and hence unable to fix nitrogen. *Rhizobium* sp. IRBG74 initially grouped as Agrobacterium but as it do not possess Ti plasmid it was re-categorized as *Rhizobium*. This bacterium contain sym-plasmid having *nif*H together with *nod*A genes and it colonizes a wide range of *Sesbania* plants. Similarly, *A. caulinodans* ORS571 is capable of nitrogen fixing endophytic colonization (Chen and Zhu 2013; Venkateshwaran et al. 2013).

Plant genotype was also found to have effect on existence and dissemination of rhizobial species in soil. For example, *Phaseolus vulgaris* and *Mimosa affinis* show difference in rhizobial nodulation specificity. *P. vulgaris* is can be nodulated by six rhizobial species, viz. *R. etli*, *R. giardinii*, *R. gallicum*, *R. tropici*, *R. leguminosarum* bv. *phaseoli* and *Bradyrhizobium* spp., whereas *Mimosa affinis* showed nodulation specificity for *R. etli* alone (Wang et al. 1999). Genistoid legumes (brooms) in Canary Islands, Morocco and Spain are nodulated by four distinct rhizobial strains viz. *B. japonicum*, *B. canariense* and two unidentified species (Vineusa et al. 2005).

Abiotic factors like pH, rainfall, soil type and temperature also influence diversity of rhizobial species, whereas soil types may influence composition of rhizobial community which is ascertained from the fact that legumes grown in different geographical locations nodulated by different rhizobial species/genera. For example, *Glycine max* (soybean) generally nodulated by *B. japonicum*; but surprisingly soybean grown in Xinjiang region of China showed colonization of root by *Mesorhizobium tianshanense* and *Sinorhizobium fredii*. Sameway, *R. leguminosarum* bv. *viciae* and bv. *trifolii* geberallly nodulates beans in Leon, France, but beans grown in Andalucia region showed presence of *R. etli*, *R. gallicum* and *S. fredii* in addition to *R. leguminosarum* bv. *viciae* and bv. *trifolii* (Velázquez et al. 2001). Conventionally, *Mesorhizobium ciceri* and *Mesorhizobium mediterranean* isolated form nodules of *Cicer arietinum*, but *Cicer arietinum* grown under water deficient conditions in Tunisia showed colonization by *Ensifer meliloti* (formerly *Sinorhizobium meliloti*) (Romdhane et al. 2009). Similarly, *E. meliloti* also been isolated from *C. arietinum* plants growing in Almora and Terai region of Uttarakhand Himalayas (Rajwar et al. 2013). Type of soil also restricts distribution and diversity of rhizobia which was clearly confirmed by characterization of different rhizobial species from Caragana plant growing in three eco-regions of China differing in soil types. *Mesorhizobium* genospecies I, II, IV, VI and VII were identified from Caragana plants growing in sandy soils of Mongolia. *M. temperatum*, *M.*

tianshanense, *M. septentrionale*, *M.* genospecies III, *R. yanglingense* and *Rhizobium* sp. IV were isolated form Caragana plants grown in saline/alkaline soils and *M. plurifarium*, *M.* genospecies V and VII, and *Rhizobium* sp. IV in fertile/forest soils of Northwestern Yunnan region (Lu et al. 2009).

Delamuta et al. (2017) evaluated phylogenetic relationship between 45 *Bradyrhizobium* strains isolated from different legumes i.e., *Arachis hypogaea*, *Acacia auriculiformis*, *Glycine max*, *Lespedeza striata*, *Lupinus albus*, *Stylosanthes* sp. and *Vigna unguiculata*, based on *nodY/K* and *nifH* genes of and compared their 16S rRNA gene phylogeny and genetic diversity by rep-PCR. 16S rRNA tree revealed that strains were dispersed into two clusters – *B. japonicum* and *B. elkanii* – with numerous strains being alike within each clade. The rep-PCR examination also discovered high intra-species diversity. Grouping of strains in the *nodY/K* and *nifH* trees was undistinguishable. Thirty nine strains obtained from soybean grouped with *Bradyrhizobium* type species and five others in distinct positions. Only one strain isolated from *Stylosanthes* sp. displayed similar *nodY/K* and *nifH* sequences to soybean strains and it also nodulated soybean. *nodC* sequences comparison showed same clusters as observed in the *nodY/K* and *nifH* phylograms. The analysis of symbiotic genes showed that a large group of strains from the *B. elkanii* superclade contained new symbiovar sojae, whereas for alternative group, comprising *B. pachyrhizi*, the symbiovar *pachyrhizi* could be projected.

7.4 Nodulation of Legume Roots

Mutualistic, nitrogen-fixing relations amongst *Fabaceae* family plants and soil bacteria *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium* and *Rhizobium* (as a group designated rhizobia) contribute considerably to crop yield. This symbiosis between legume plants and rhizobia also offers an interesting model to study the intricacy of various mechanisms that control plant cell partition and nodulation. In the absence of the host, free-living rhizobia are in their saprophytic phase and compete with other soil microflora for limited nutrient resources. The population densities of rhizobia are usually low when legumes are not a large component of the plant community (Woomer et al. 1988; Kucey and Hynes 1989), demonstrating that symbiotic form is crucial for formation of a considerable saprophytic inhabitants of rhizobia in the soil. Natural rhizobial population as well as inoculated rhizobia was found to be different in their tolerance to key environmental clues and thereby influence persistence and existence of distinct species in soil (Vidor and Miller 1980; Defez et al. 2017).

Nodulation (*nod*) genes of rhizobia required for infection and nodulation are classified as universal, host-specific and regulatory *nod* genes (Fig. 7.2). Nodulation genes are principally classified into three classes: (a) regulatory *nod*D and *nod*VW genes enabling activation of and host specific *nod* gene transcription, (b) the common *nod*ABC, *nod*M and *nod*IJ genes, which are functionally and physically conserved amongst different rhizobia, and (c) host specific *nod* genes, which are variable with bacterial species and strains. Alteration of host specific *nod* genes

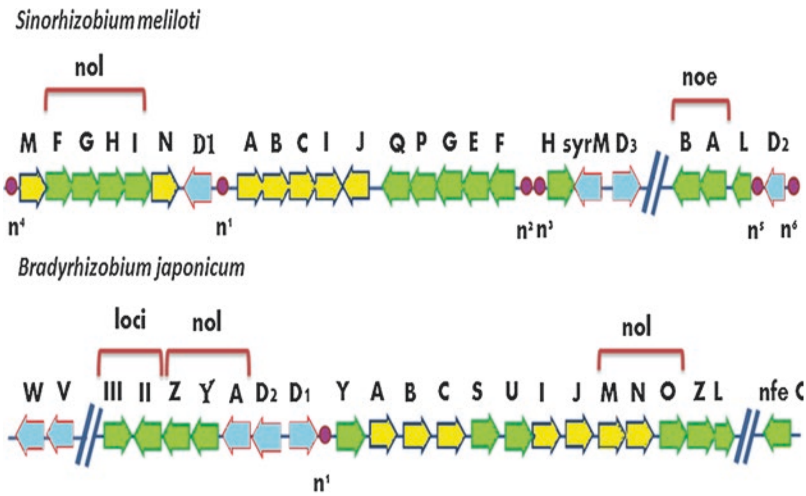

Fig. 7.2 **Nodulation genes (*nod*, *nol*, *noe*) of *Sinorhizobium meliloti* and *Bradyrhizobium japonicum*** are represented. Universal nodulation genes are depicted in yellow colour and regulatory nodulation genes are shown in light blue colour, whereas host-specific nodulation genes are shown in light green colour. Regulatory *nod*D product interact with specific flavonoids, then binds with *nod* boxes (n′) and cause activation of transcriptional operon of other nodulation genes

generally do not counterpart with cloned genes from other rhizobia. The structural arrangement and regulation of nodulation genes of *Rhizobium, Bradyrhizobium* and *Azorhizobium* has been reviewed recently (Long 1996; Spaink 1996; Hanin et al. 1999; Appelbaum 2018). Expression of structural *nod* genes was governed by flavonoid signals from plants transcription of *nod*D regulatory gene is regulated by specificity of flavanoids and hence believed to be partial determining factor of strain/host specificity. The common *nod* genes are involved in manufacturing of basic lipochitin-oligosaccharide molecule and host specific nodulation genes add various substituents at reducing or non-reducing ends of Nod factors (Perret et al. 2000; Sindhu and Dadarwal 2001a, b, c). Alteration of host specific *nod* genes may end in either a postponement in nodulation or a variation in host range (Denarie et al. 1992). Expression of structural *nod* genes results in synthesis of specific extracellular lipo-oligosaccharide compounds termed as nodulation factors (NF) which stimulate root-hair deformation, cortical cell division and other responses in prone legume root.

Legume roots release flavonoids in the root exudates and rhizobia which colonize soil in neighborhood of root hair are attracted through chemotaxis in response to the flavonoids. The flavonoids and isoflavonoids secreted by roots of legumes bind with the regulatory protein NodD, which subsequently bind to conserved *nod*-box in the promoters of bacterial nodulation genes to encourage their expression. The *nod* genes code for enzymes for synthesis of Nod factors. Strain-specific combinations of nodulation genes (nod, nol or noe) code for addition of several decorations to core structure (Sindhu et al. 1999a, b). Examples of NF substituents are

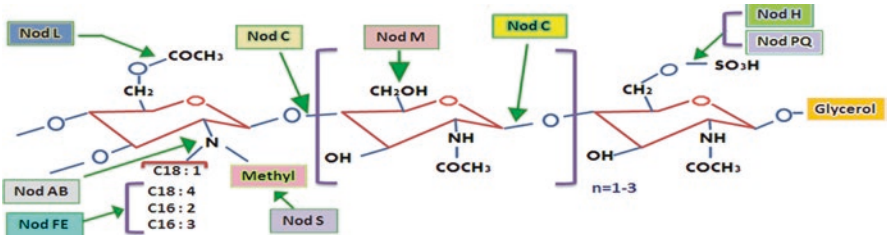

Fig. 7.3 Nodulation factor synthesized by *Rhizobium* strains. Host specific nodulation genes (*nod*, *nol* or *noe*) results in several decorations or modifications on the basic core structure

hydrogen (R1–R6), carbamoyl (R1–R3), acetyl (R1–R4), sulfate (R4), fucose (R4) and arabinose (R6) (Fig. 7.3). The perception of NFs by the plant in turn triggers several early symbiotic reactions in the plant root, for example ion fluxes, calcium spiking, root hair deformation, cortical cell division and synthesis of an infection thread that directs the bacteria to the emerging primordium. Several elements of signaling pathway leading to nodulation have been characterized: the putative NF receptors (which belong to the lysine motif receptor-like kinase family, LysM–RLK), a cation channel, a leucine-rich repeat receptor kinase (LRR–RK), a calcium/calmodulin-dependent protein kinase (CCaMK), a cytokinin receptor and various transcriptional factors. Transmembrane Nod factor receptors recognize Nod factor in a strain- and ecotype-specific manner. Alteration of Nod factor such as the length and saturation of the acyl group determine host specificity. Nod factor receptor activation stimulates root hair deformation enabling them to lodge small number of bacteria which further grow in to a colony within nodule. Modulation of host range was also done through surface polysaccharides such as EPS from *S. meliloti*. Recognition of polysaccharides by R genes present in some ecotypes or varieties of plants restricts host range which culminate in the transcriptional activation of other *nod* genes (Downie 1994; Russelle et al. 2008).

Rhizobia encourage formation of nodules on legumes by either a NF-dependent or a NF-independent process. Gully et al. (2017) reported whole genome sequence of *Bradyrhizobium* sp. strain ORS285, capable of nodulating *Aeschynomene* legumes using two different approaches that vary in requisite of Nod factors. In NF strategy, plant signals of the flavonoid family are received by bacterial NodD regulatory proteins that encourage synthesis of lipochitooligosaccharidic NFs that activate nodule organogenesis (Oldroyd and Downie 2008). Some steps of this process are subject to variation: (i) alternative plant compounds (e.g. betaines, jasmonate, xanthones, vanillin, etc.) can start *nod* gene expression but these compounds usually act at higher concentrations than (iso) flavonoids (Cooper 2007); (ii) beside NodD, additional regulators can modulate expression of *nod* genes like NolR (in some *Rhizobium* and *Sinorhizobium* species) or NolA and the two component system NodV/NodW (in *Bradyrhizobium japonicum*); and (iii) synthesis of the Nod factor support is regulated by canonical *nod*ABC genes existing in all rhizobia.

The rhizobia adhere to root hairs all over the root but root hairs that are most responsive to *Rhizobium* infection are just behind the apical meristem at the site of emergence of root hairs. In the infectible root zone, rhizobia adhere to surface of root hair either through an acidic extracellular polysaccharide or via definite calcium-dependent protein, rhicadhesin, cellulose fibrils (Mateos et al. 1995; Smit et al. 1987) and legume root lectin (Kijne et al. 1988). Lipooligosaccharides (Nod factors) produced by the infecting rhizobia cause characteristic curling and deformations of root hair and cortical cell divisions in well-suited host (Lerouge et al. 1990; Broughten et al. 2000). The deformed root hairs in various legumes may form different structures, including corkscrews, branches, twists, spirals and shepherd's crooks. Cao et al. (2017) described that a stable regulation of innate immunity is probably essential during process of nodulation starting from rhizobial infection, symbiotic establishment and maintenance. Following initial infection processes, plant immune responses can also be stimulated in nodules and expected to result in nodule senescence. Mutualism believed to be derived from a pathogenic relationship that reduced over time to a condition in which both partners can benefit. Generally rhizobia overcome host immune response by actively suppressing it to permit infection and symbiosis establishment. Whereas plants developed mechanisms to limit nutrient supply to symbiont and thereby checking number of nodules on plant so that protecting themselves form overburden.

In *Medicago sativa*, nodule development is closely linked to Nod factor (NF) synthesis by *S. meliloti* (Lerouge et al. 1990). *S. meliloti* starts two analogous, nodule-specific, procedures to develop unspecified nodules nearby root proto-xylem ends: (i) rhizobial colonization pathway, that includes infection thread development in root hairs and cortical cells, and (ii) nodule organogenesis pathway, that includes stimulation of cell divisions in root cortical, endodermal and pericycle cell layers to generate a nodule primordium and then, a nodule meristem (Timmers et al. 1999; Xiao et al. 2014; Djordjevic et al. 2015). Rhizobial NFs hurriedly trigger nuclear calcium oscillations in root hair cells (Levy et al. 2004; Miwa et al. 2006), which transcriptionally activates central symbiotic (SYM) genes e.g. nodule commencement (MtNIN), nodulation signaling pathway 1 and 2 (MtNSP1 and 2) (Kaló et al. 2005; Smit et al. 2005) and MtCLV3/ESR-related 12 and 13 (MtCLE12 and 13) (Mortier et al. 2010; Saur et al. 2011). Nodulation is also positively and negatively controlled by complex communications with numerous hormones and peptides (Mortier et al. 2010, 2012; Larrainzar et al. 2015; van Zeijl et al. 2015). Together, these signals, along with NF/SYM pathway, control nodulation process and frequency on root system (Oldroyd 2013). A large number of infection threads will not result in to nodule formation (Djordjevic et al. 1986) which shows effect of negative regulatory routes facilitated by ethylene-related and CLE-related pathways (Kassaw et al. 2015).

The rhizobia occupy root hair cell by means of host-derived infection thread, which is usually initiated from the most acutely curled region, starting as invagination of root hair cell membrane (Fig. 7.4). Rhizobia move down in root hair to cortical cell layers by interiorly budding tube-like infection thread. Rhizobia in infection thread are surrounded by mucigel composed of cell wall polysaccharides, plant-derived matrix glycoprotein and rhizobial exopolysaccharides (Callaham and Torrey 1981; Broughten et al. 2000). Growth of infection thread continues towards newly

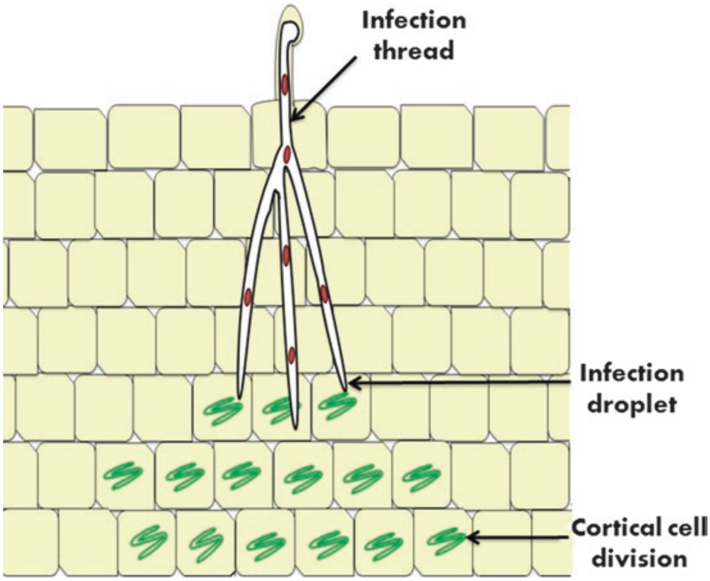

Fig. 7.4 Nodulation factor secreted by rhizobia cause root hair deformation. Rhizobia occupy root hair cell by means of a host-derived infection thread

synthesized nodule primordium which is produced by stimulation of mitotic activity in root cortex as a result of rhizobial Nod factors that afterward develops into the nodule meristem (Dudley et al. 1987). Infection thread branches and leads towards cortex and a clearly apparent nodule grow on root. Nodules may have one or more rhizobial strains and can be either determinant (lack a persistent meristem and are spherical) or indeterminate (situated at distal end of cylindrically shaped lobes) (Russelle et al. 2008). Many infections are terminated due to a failure in communication between rhizobia and the host plant leading to strict regulation of nodule number by the plant. In the root cortex, infection threads branch and enter in to individual nodule cells and a new structure, infection droplet, is formed and rhizobia get released into nodule tissue cells by a process that is similar to endocytosis (Roth and Stacey 1989a) and then occupy an organelle-like cytoplasmic compartment, designated as "symbiosome", which is surrounded by a plant-derived peribacteroid membrane (Roth and Stacey 1989b). This process keeps microbes "outside" the plant where rhizobia are intracellular but extracytoplasmic. Peribacteroid membrane-enclosed bacteria divide until cytoplasm of every infected plant cell comprises several thousand rhizobial cells. In late symbiotic zone, infected cells are entirely occupied with bacteria that have differentiated into their pleomorphic endosymbiotic bacteroids (Brewin 1991) especially express nitrogen fixation genes. The plant uses the fixed nitrogen as nitrogen source and delivers bacteroids with photosynthates and amino acids as carbon, energy and nitrogen sources.

In the nodule primordium, rhizobia are released from infection droplet which gets differentiated into nitrogen-fixing bacteroids.

The preset senescence of nitrogen-fixing bacteroids is fundamental portion of growth sequence in indeterminate nodules (Vasse et al. 1990). At this stage, growth and division of bacteroids is ceased and lysis of N_2-fixing bacteroids as well as host cells occurs. In recent times some papain-like and legumain-like cysteine proteases, also known as vacuolar processing enzymes (VPEs), were recognized that were intensely expressed throughout the development of nodule senescence (van Wyk et al. 2014). In nodules, papain-like cysteine proteases have known functions in the regulation of bacterial symbiosis, nitrogen fixation and leghemoglobin synthesis (Vande Velde et al. 2006; Li et al. 2008). Inhibition of papain-like cysteine protease activity was found to increase soybean tolerance to drought and favoured increased nodulation (Quain et al. 2014, 2015). VPEs found to be a part in age-linked senescence and triggering of pre-proteases. With their caspase-like activity, they additionally play significant part in programmed cell death (Hara-Nishimura et al. 2005; Roberts et al. 2012). At the death of a nodule, the bounded rhizobia are exclusively positioned to obtain the plant nutrients from senescing nodule tissues to proliferate rapidly. The number of nodule-derived rhizobia entering the soil population, becomes low as numerous rhizobial cells get destroyed together with plant cells during nodule senescence (Pladys et al. 1991) and also, differentiated bacteroids could not easily shift from biotrophic to saprotrophic life in soil (Quispel 1988).

7.5 Mechanisms of Plant Growth Promotion by Rhizobia

Rhizobia acts through direct and indirect mechanisms for improvement of crop growth and yield (Fig. 7.5). Direct mechanisms for plant growth promotion includes nitrogen fixation (Machado et al. 2013), nutrient solubilization/mobilization or mineralization (Reimann et al. 2008; Yu et al. 2012; Abd-Alla 1994a; Kumar and Ram 2014; Prasad et al. 2015), production of phytohormones, vitamins etc. (Sahasrabudhe 2011; Ghosh et al. 2015; Jangu and Sindhu 2011) (Table 7.2). In addition to symbiotic N_2 fixation, rhizobia also carry out non-symbiotic N_2 fixation in association with non-legume plants. Nitrogen fixation by photosynthetic bradyrhizobia was observed in association with wild rice (Chaintreuil et al. 2000). In indirect mechanism rhizobia produces bioactive molecules which inhibits phytopathogens (Datta and Chakrabartty 2014; Sindhu et al. 2014, 2017). Functionally different plant growth promoting rhizobacteria under variable environmental situations and in crop cultivation systems may enable growth and development of plants using either one or multiple mechanisms of plant growth promotion.

7.5.1 Biological Nitrogen Fixation

Fixation of atmospheric nitrogen by microorganisms is significant constituent of sustainable agriculture systems (Sessitsch et al. 2002; Karunakaran et al. 2009). *Rhizobium* are well known for establishment of symbiotic association with leguminous crops (Patriarca et al. 2002; Gage 2004) forming nodules to transforms

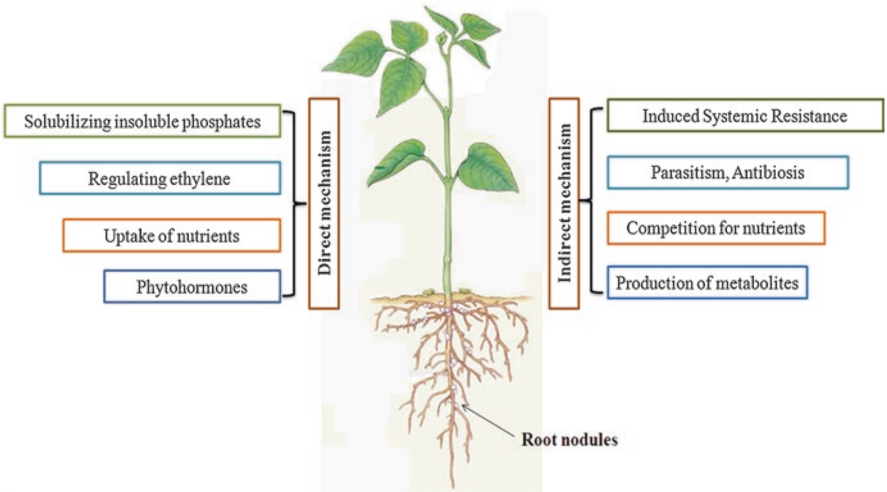

Fig. 7.5 Diagrammatic representation illustrating the direct and indirect mechanisms of plant growth promotion by rhizobia

atmospheric nitrogen in to ammonia and make it available to plants. In symbiotic relationship leguminous plants provides energy and photosynthetic materials to bacteria and bacteria in turn provide nitrogen to plants for incorporation into cellular constituents like amino acids, proteins and other essential nitrogenous compounds (Gresshoff 2003).

Nodules are generally termed as nitrogen fixation factories and millions of bacteroids inside the nodules fix the atmospheric nitrogen continually. Moreover, number of nodules formed on host plant is usually linked with amount of nitrogen fixed in particular *Rhizobium*-legume association. However, the number of nodules formed on a particular legume plant varies in different *Rhizobium*-legume systems. For example, the number of nodules formed ranges from 25–50 under sterilized chillum jar conditions in summer legumes such as green gram (*Vigna radiata* L. Wilczek), cow pea [*Vigna ungulculata* (L.) (Wilczek)], black gram [*V. mungo* (L.) (Hepper)]. Usually, 5–20 nodules are formed on cluster bean [*Cyamopsis tetragonoloba* (L.) (Taub)] and pigeon pea (*Cajanus cajan*). On the other hand, 30–60 nodules are usually formed under sterilized conditions on winter legume chick pea [*Cicer arietinum* (L.)] (Fig. 7.6). Large number of small nodules (50–120) is formed in ground nut (*Arachis hypogea*). Various environmental factors such as addition of nitrogenous fertilizers to the legume crops and level of ethylene formed due to hydrolysis of ACC in the root environment has been found to adversely affect nodulation under field conditions. Varin et al. (2009) reported that N fertilisation repressed nitrogen fixation in clover but N_2 fixation was improved by addition of sulphur (S). Sulfur fertilization improved the nodule length and number of nodules containing leghaemoglobin. Sulphur fertilization, improved photosynthesis and vegetative reproduction in white clover directly and indirectly through increase in

Fig. 7.6 Nodules formed on chick pea (*Cicer arietinum*) plant under sterilized chillum jar conditions

nitrogen fixation. Sulfur dependent response allows plants to adapt to variety of abiotic conditions but its sensitivity to S nutrition would be a shortcoming for rivalry in a state of soil sulphur poverty. Whereas, S fertilization could help sustain such plants under nitrogen limiting status.

Mathews and Carroll (2018) reported that many edaphic factors such as pH, nutrient deficiencies and toxicities, water, and temperature affect nodulation, but nitrate is unique in that it is generally not inhibitory to plant growth. Estimates of energy costs are generally greater for nitrogen fixation than for nitrate assimilation. Besides this, there are other developmental and ecological considerations which may have resulted in natural selection for nitrate inhibition of nodulation. Nitrate can be assimilated in either, or both, root and shoot tissue of plant, whereas nitrogen fixation needs development of a specific organ, root or stem nodule. In young white clover seedlings, for example, maximum activities of nitrate reductase precede the highest rates of nitrogenase activity by a matter of weeks. Indeed, plants that are dependent on nitrogen fixation as the sole nitrogen source do not grow as well as those which are supplemented with low noninhibitory or larger levels of nitrate. In the ecological context, it can be assumed that nitrate utilization by legumes decreases the amount of soil nitrate available to adjacent nonsymbiotic plants that are competing for other nutrients. Thus, preferential utilization of nitrate may be advantageous for legume species by decreasing the competitive ability of other plants that are unable to form a nitrogen-fixing symbiosis.

Sindhu and Dadarwal (2001c) evaluated efficiency of mutant *Rhizobium* strains for nodulation on chick pea (*Cicer arietinum*) grown in sterilized chillum jars. Mutants of strains Ca85 and Ca401 showed no nodulation efficiency whereas mutants of strains Ca181 and Ca534 were not able to nodulate the roots and also unable to fix nitrogen. Further mutants also displayed reduced nodulation and nitrogenase activity which in turn showed decreased shoot dry weight as compared to inoculation of wild type strains. Overall, it was concluded that acquirement of streptomycin resistance in *Rhizobium* sp. *Cicer* strains showed decreased symbiotic efficiency of the microbial strain in chick pea.

Nitrogen fixation capacity of the *Rhizobium* strains is usually deliberated as one of the key character affecting plant growth. Nitrogen fixation is detected either by growth of the organisms to grow on nitrogen free medium and can be measured via ^{15}N incorporation (^{15}N enrichment) and acetylene reduction. Urban et al. (1986) prompted *Rhizobium trifolii* strain 0403 in nitrogen free medium by treating the cells with 16.6 mM succinic acid and other nutrients and observed that organisms grew luxuriously on semisolid or liquid medium and fix nitrogen to satisfy their own requirement. Nitrogen fixation was determined through ^{15}N incorporation (18% ^{15}N enrichment in 1.5 doublings) and acetylene reduction. Nitrogen-fixing cells showed a maximum specific nitrogenase activity of 5 nmol of acetylene reduced/min/mg of protein at 0.04 atm (ca. 4.05 kPa) and 3% oxygen concentration in liquid medium. The generation time of organisms in liquid medium at 30 °C was 1–5 days, depending on oxygen concentration. Nodulation studies by *Rhizobium trifolii* strain 0403 in the white clover showed *in vitro* nitrogenase activity indicating that at least portion of population retained characteristics of wild-type strain 0403.

During nitrogen fixation, enzyme nitrogenase catalyzes reduction of nitrogen to ammonia concomitant reduction of protons to hydrogen. The energy loss in proton reduction leading to H_2 evolution varies from 40 to 60% in the absence of an active uptake hydrogenase. Some of the *Rhizobium* strains have been identified, which has the capability to oxidize the evolved H_2 leading to more nitrogen fixation. Dadarwal et al. (1985) surveyed *Rhizobium* strains nodulating summer legumes cow pea [*Vigna ungulculata* (L.) (Wilczek)], black gram [*V. mungo* (L.) (Hepper)] and cluster bean [*Cyamopsis tetragonoloba* (L.) (Taub)] and a winter legume chick pea [*Cicer arietinum* (L.)] in Northern Plains of India and screened for hydrogenase activity to determine distribution of Hup character in the native ecosystem. Around 56% of *Rhizobium* strains of summer legumes were Hup^+ winter legume, chick pea, was all Hup^-. Ex planta acetylene reduction activity was observed in most of the Hup^+ but not in the Hup^- strains of any of the host species. In summer legume, mixed inoculation of Hup^+ and Hup^- strains under sterilized as well as unsterilized soil conditions, showed that the host species were predominantly nodulated with Hup^+ strain.

Sindhu and Dadarwal (1986) reported that reduction of triphenyl tetrazolium chloride and methylene blue dyes reduction tests were ambiguous for detection of Hup character in *Rhizobium* strains isolated from green gram, black gram, cow pea, pigeon pea, cluster bean and chick pea. Hup^+ *Rhizobium* strains isolated from these legumes except Hup^- strains obtained from chick pea (*Cicer arietinum*) invariably expressed nitrogenase activity under cultural conditions. Characterization of native *Rhizobium* strains on the basis of *ex planta* nitrogenase induction showed that 94% of the *ex planta* nitrogenase positive isolate were of Hup+ phenotype, whereas all the *ex planta* nitrogenase negative isolates were of Hup^- phenotype in nodules. The expression of nitrogenase under cultural conditions was therefore, found to be a reliable method for identification of *Rhizobium* strains for Hup^+ phenotype among the rhizobia of the "cowpea miscellany". Mutants were derived from *Rhizobium* strains of cowpea miscellany *Vigna* group i.e., S24 and GR4 having ability to express ex-planta acetylene reduction activity (ARA) after mutagenesis with nitrosoguanidine (Sindhu and Dadarwal 1992). Approximately, 70% of the mutants of strain S24 and 82% mutants of strain GR4 were found to have increased ex-planta ARA in comparison to their respective parent strains. Six mutants of strain S24 and four of GR4 strain with increased ex-planta ARA were selected to study in planta H_2 uptake and symbiotic performance in two host species: green gram (*Vigna radiata*) and black gram (*Vigna mungo*). Most of mutants showed increased H_2 uptake in nodules and symbiotic affectivity of these selected mutants was also higher than the parent strain in both the legumes. The authors suggested that it is possible to obtain symbiotically superior mutants by mutagenesis taking desirable ex-planta character for initial selection followed by plant test.

Saini et al. (1996) isolated native rhizobia from root nodules of *Sesbania bispinosa* and from root and stem nodules of *S. rostrata. Rhizobium* strains were studied for occurrence of hydrogen uptake system (Hup), nitrate respiration (NR), *ex planta* expression of nitrogenase and relative symbiotic efficiency in relation to Hup and NR activities. The rhizobia of both the host species were found to have two types of uptake hydrogenases: (i) recycling hydrogenase activity expressed *ex planta* as well as *in planta* in nodules and (ii) hydrogenase activity expressed only in nodules but not under cultural conditions. Dissimilatory nitrate reduction leading to complete denitrification was found to be common among both Hup^+ as well as Hup^- isolates. *Ex planta* nitrogenase activity was not observed in any isolates from both the *Sesbania* species. Symbiotic effectivity of Hup^+ isolates was at par with Hup isolates. There was no specificity with regard to host infectivity and the stem nodulating rhizobia from *S. rostrata* formed root nodules on *S. bispinosa* as well as on *S. rostrata*.

The amount and type of carbon sources, nitrogen level in growth medium, temperature and growth conditions have been found to affect expression of nitrogenase and hydrogenase enzymes. Sindhu and Dadarwal (1988) observed influence of temperature on nitrogenase and uptake hydrogenase activities in nodules of green gram (*Vigna radiata* L. Wilczek), black gram (*V. mungo* L. Hepper) and chick pea (*Cicer arietinum* L.), inoculated with different *Rhizobium* strains at three different temperatures. The optimum temperature for nodule nitrogenase activity was 35 °C in green gram and black gram (summer legumes), while it was below 25 °C, in the case of chick pea (winter legume). A majority of the Hup^+ *Rhizobium* strains of the summer legumes had H_2 recycling ability that recycled the evolved H_2 produced in nodules by nitrogenase. With increase in temperature from 15 to 35 °C, the H_2 uptake rates also increased in nodules. In nodules formed with Hup^- strains, although the H_2 evolution rates increased with increase in temperature in all the three legumes, however, green gram and black gram nodules (summer legumes) evolved significantly higher amounts of H_2 than chickpea (winter legume). Also, irrespective of temperature optima for ARA, at lower temperature, the relative efficiency was high in all the three legumes. Sindhu and Dadarwal (1995a) determined nodule nitrogenase and H_2 uptake activities in normal (undecapitated) and decapitated plants (removal of shoot 24 h before measurements) of green gram and black gram inoculated with two Hup^+ *Rhizobium* strains which had H recycling ability in excess to the rates of H_2 produced by nitrogenase in nodules. A significant decline in nodule nitrogenase activity was observed in decapitated plants as compared to uncut control plants at 40 and 50 days of plant growth. However, nodules of both, control and decapitated plants, of both host species showed hydrogen supported enhanced acetylene reduction activity (ARA). The H_2 uptake rates of the two strains varied depending on host as well as on stage of plant growth. However, based on the relative ratio of H consumed per mole of C_2H_2 reduced in case of normal photosynthate supply as well as from the interruption of photosynthate supply (decapitated plants), it appears that photosynthate supply remains a limiting factor in nitrogen fixation under normal conditions of plant growth during symbiosis.

7.5.2 Production of Plant Growth Regulators

Plant growth regulators are organic compounds like plant hormones that stimulates plant's physiological response at lower concentration and hence effect plant development. Based on chemical structures and mode of action, plant growth regulators are grouped into six different categories i.e., auxins; cytokinins; gibberellins; ethylene; inhibitors (abscisic acid, phenolics and alkaloids) (Ferguson and Lessenger 2006; Mishra et al. 2006); and brassinosteroids (Rao et al. 2002; Bajguz and Tretyn 2003). Concentration of plant growth regulators produced by PGPR may vary from organism to organism. Majority of PGPR and symbiotic rhizobia influence plant growth by production of auxins, cytokinins and gibberellins, strigolactones, abscisic acid and brassinosteroids.

7.5.2.1 Auxins

About 80 % of the PGPRs and rhizobia produces most efficient biomolecule for plant growth promotion i.e. auxins (Antoun et al. 1998; Schlindwein et al. 2008; Bhagat et al. 2014). Major classes of auxins synthesized by soil microbes includes indole acetic acid (IAA), indole butyric acid or analogous compounds resulting from tryptophan metabolism (Loper and Schroth 1986; Malik and Sindhu 2008; Solano et al. 2008). Auxins are phyto-hormones that encourage cell division and elongation. Vargas et al. (2009) reported a considerable difference in auxin production amongst rhizobial isolates from arrow leaf clover (*Trifolium vesiculosum*) white clover (*T. repens*) nodules. Arrow leaf clover isolates showed IAA production frequency in more than 90% isolates whereas only 15% isolates showed IAA production. IAA producing rhizobia showed more intense nodule formation as auxins was reported to influence nodulation process (Boiero et al. 2007). IAA alters root morphology by increasing number of secondary roots and thereby increasing surface area as well as size and weight of roots. Which ultimately results in to improvement of more extensive root architecture of legume plants (Dazzo and Yanni 2006). Inoculation with auxin-producing bacteria may also result in the formation of adventitious roots (Solano et al. 2008). Modification in root architecture by rhizobacterial IAA enhance nutrient absorption by plants which ultimately results in to enhancement of plant growth (Probanza et al. 1996). Similarly, Biswas et al. (2000) reported that inoculation of rice with *R. trifolii* improved dry matter and grain production, in addition to augmentation in N, P, K and Fe content in plant tissue.

7.5.2.2 Cytokinins and Gibberellins

Cytokinins influence cell division and cell enlargement, in addition to influencing seed dormancy, flowering, fruiting and plant senescence (Ferguson and Lessenger 2006). Certain strains of *Rhizobium* synthesize cytokinins in culture but is quantification and characterization was not possible (Sturtevant and Taller 1989; Wang et al. 1982) but it is found to be involved in nodule formation by rhizobia (Frugier et al. 2008) via an unknown mechanism. Gamas et al. (2017) reviewed that cytokinins were involved in the precise identification of symbiotic associates, beginning of bacterial infection in root hair cells and commencement of nodule in root cortex. Progressively multifaceted regulatory networks was found in which cytokinin (CK) play critical functions in various phases of primary symbiotic stages. Interestingly, these parts can be positive or negative, cell independent or non-cell independent, and differ, relying on time, root tissues and probably legume species. Current progresses showed interconnected role of cytokinines in establishment of symbiotic relationship with other signaling pathways during nodule initiation. Gibberellins improve seed germination (Miransari and Smith 2009), encourage general growth of plants and postpones aging (Ferguson and Lessenger 2006). Production of lower concentration of gibberellins documented from *Rhizobium* (Solano et al. 2008). Several reports showed free-living rhizobial strains can produce small quantity of gibberellin like substances. Gibberellin was also believed to play a key role in *Rhizobium*-legume symbiosis that may be significant suggestions to endophytic colonization of non-legumes by rhizobia. For example, infection of *A. caulinodans* in *S. rostrata* was through intercellular crack entrance facilitated by gibberellins which is key process of endophytic colonization of non-legumes by rhizobia and gibberellins produced by bacteria may simplify this process (Lievens et al. 2005).

7.5.2.3 Strigolactones

Strigolactones (SLs) play a key part in governing root growth, shoot branching and plant-symbionts interaction (Rehman et al. 2018). Strigolactones produced by rhizobia and PGPRs have been found to affect nodule development. The presumed constituents of SL synthesis enzymes *GmMAX1a* and *GmMAX4a* with tissue expression patterns were identified and governed by rhizobia infection and modified throughout nodule formation. Knockdown transgenic hairy root soybean lines of *GmMAX1a* and *GmMAX4a* displayed reduced nodule number due to less expression of numerous nodulation genes necessary for nodule formation. Hormone analysis showed that *GmMAX1a* and *GmMAX4a* knockdown hairy roots showed increased level of ABA and JA but considerably reduced auxin content. This study showed close interactions between SL and other hormone signaling in controlling plant development and legume-rhizobia interaction.

7.5.2.4 Abscisic Acid and Brassinosteroids

ABA produced by certain strains of rhizobia like *B. japonicum* USDA110 (Boiero et al. 2007) can provide drought tolerance to plants to some extent. However, increase of ABA concentration also showed negatively effect on nodule development in *Trifolium repens* and *Lotus japonicas*. Suzuki et al. (2004) showed inhibition of nodulation in plants inoculated with *R. trifolii* and latter supplemented with ABA. Inoculation of *L. japonicus* mutant that has lesser sensitivity to ABA, (Tominaga et al. 2010) caused improved nodulation in *M. loti* inoculated plants.

Brassinosteroids are the new group of hormones and having steroidal substances which enables plants to resist abiotic stresses. Brassinosteroids generally found to affect processes such as seed germination, rhizogenesis, flowering, senescence, abscission and maturation (Rao et al. 2002). Vardhini and Ram Rao (1999) showed that treatment of brassinosteroids in groundnut gave better nodule formation and nitrogen fixation (*Arachis hypogaea*) developed in natural soil (without inoculation of *Rhizobium*).

7.5.3 Amelioration of Abiotic and Biotic Stress by Rhizobia

Climate change is the greatest threat to world's agricultural sustainability in the twenty-first century. Drastic changes in various climatic conditions increase the incidence of abiotic and biotic stresses, which can tremendously influence the global decrease in productivity of agricultural and horticultural crops (Grover et al. 2011; Papworth et al. 2015). Global warming and alteration in precipitation patterns, lead to several abiotic stresses like extremes temperatures, drought, flooding, salinity, metal stress and nutrient stress that creates harmful effects on food production (Barrios et al. 2008; Selvakumar et al. 2012). The probability of occurrence of extreme climatic events has increased in the last couple of decades and farmers lack the management options to sustain the agricultural productivity (Kalra et al. 2013). Abiotic stress hamper growth and production of crop, causing land degradation by making soil nutrient deficient and more stress prone. The abiotic stresses are usually interconnected with one another and function as a chain due to climatic variations (Grover et al. 2011).

The improvement in crop yields under unfavourable conditions by classical breeding or gene transfer techniques pose certain limitations in terms of ethical issues and time requirements (Ashraf and Akram 2009; Fleury et al. 2010). Again, drought stress tolerance is often a complicated phenomenon involving clusters of gene networks. Apart from classical breeding and transgenic approaches, application of plant growth promoting rhizosphere (PGPR) bacteria is an alternative eco-friendly strategy for improving plant fitness under understressed environments (Kim et al. 2012) (Table 7.3). Application of beneficial rhizosphere bacteria has recently been found to alleviate the abiotic stresses. Some bacterial species such as *P. polymyxa*, *Achromobacter piechaudii* and *R. tropici* provide tolerance to drought stress in *Arabidopsis*, tomato (*Solanum lycopersicum*) and common bean (*Phaseolus vulgaris*), respectively through accumulation of abscisic acid and due to degradation of reactive oxygen species and ACC (1-aminocyclopropane-1-carboxylate) (Mayak et al. 2004b; Yang et al. 2008). Salinity tolerance in plants is conferred by application of *A. piechaudii* and *B. subtilis* (Mayak et al. 2004a; Zhang et al. 2006).

Figueiredo et al. (2008) identified enhanced antioxidant enzymatic activity in common bean plants (*Phaseolus vulgaris* L.) coinoculated with *R. tropici* and *P.*

Table 7.3 Inoculation effect of rhizobia on ameliorating the influence of various stresses in different crops

Rhizobium spp.	Host plant	Proposed mechanism(s)/ plant response	References
Drought stress			
Rhizobium spp.	*Zea mays*, *Triticum aestivum*	Encouraged drought tolerance by catalase enzyme, exopolysaccharide and IAA production	Hussain et al. (2014a, b)
Rhizobium spp., *Glomus mosseae*, *Glomus intraradices*	*Phaseolus. vulgaris*, *Zea. mays*	Enhanced growth, yield and relieved moderate drought stress	Franzini et al. (2013)
Rhizobium gallicum 8a3	*Phaseolus vulgaris*	Controlled water relations in plant	Sassi-Aydi et al. (2012)
Mesorhizobium tianshanense, *G. intraradices*	*Lotus tenuis*	Variation of proline and polyamine	Echeverria et al. (2013)
Rhizobium galegae HAMBI 1141, *Pseudomonas trivialis* 3Re27	*Galega officinalis*	Enhanced root tip colonization	Egamberdieva et al. (2013)
Rhizobium strains RhOF4 and RhOF6	*Vicia. faba*	Regulated enzymes of ascorbate-glutathione cycle and decreased glutathione	Oufdou et al. (2014)
Temperature stress			
Rhizobium sp.	*Prosopis juliflora*	Enhanced symbiosis and nitrogen fixation	Kulkarni and Nautiyal (2000)
Bradyrhizobium strains	*Glycine max*	Effective nitrogen fixation at high temperatures	Rahmani et al. (2009)
Mesorhizobium sp.	–	Improved transcriptional induction of chaperone genes	Alexandre and Oliveira (2011)
Heavy metal stress			
B. japonicum E109	*Glycine max*	Decreased symbiosis due to arsenic toxicity	Talano et al. (2013)
Rhizobium, *Sinorhizobium* spp.	*Lathyrus sativus*, *Lens culinaris*, *Medicago truncatula*, *M, minima*	Phytoremediation of Cd-contaminated soil	Guefrachi et al. (2013)
Cupriavidus necator	*Leucaena leucocephala*, *Mimosa pudica*, *Mimosa caesalpiniaefolia*	Bioremediation of Zn-, Cu-, Pb-, and Cd-contaminated soils	Ferreira et al. (2013)
Rhizobium spp.	*Lens culinaris*	Reduced uptake of Ni in contaminated soil and enhanced plant growth	Wani and Khan (2013)
Rhizobium MuJs10A	*Vigna radiata*	Improved nodulation efficiency	Mondal et al. (2017)

(continued)

Table 7.3 (continued)

Rhizobium spp.	Host plant	Proposed mechanism(s)/ plant response	References
Biotic stress			
Mesorhizobium loti	*Brassica campestris*	Suppression of white rot disease/*Sclerotinia sclerotiorum*	Chandra et al. (2007)
Rhizobia	*Cicer arietinum*	Suppression of *Rhizoctonia solani*	Hemissi et al. (2013)
R. leguminosarum strain RhOF4	*Vicia faba*	Reduction in influence of cyanotoxin biohazard	Lahrouni et al. (2013)
Rhizobium sp. *cicer* strain Ca181	*Cicer arietinum*	Improved nodulation and growth of chickpea along with decrease in wilt frequency	Khot et al. (1996)
Mesorhizobium ciceri	*Cicer arietinum*	Suppression of *F. oxysporum*, synthesis of IAA and siderophores	Yadav et al. (2015)

polymyxa under drought stress conditions. Treatment of pea plants with *Pseudomonas* spp. containing ACC deaminase somewhat removed effects of drought stress (Arshad et al. 2008). Similarly, treatment of tomato (*Solanum lycopersicum* L.) and pepper (*Capsicum annuum* L.) seedlings with *A. piechaudii* ARV8 decreased the production of ethylene (ET) that may have contributed to the observed drought tolerance (Mayak et al. 2004b). Lim and Kim (2013) showed that pepper plants treated with *B. licheniformis* K11 withstand drought stress and had better survival compared to non-treated plants. The observed drought tolerance was attributed to ACC deaminase production by PGPR that reduced ET concentrations by cleaving ACC.

Efficiency of *Bradyrhizobium* strains for alleviating effect of water stress was assessed in peanut genotypes through determination of antioxidant enzymes activities, leaf gas exchanges and vegetative growth in greenhouse with three peanut genotypes (BRS Havana, CNPA76 AM and 2012-4) (Barbosa et al. 2018). In experiment two *Bradyrhizobium* strains (SEMIA6144 and ESA123) under two levels of irrigations i.e. with and without irrigation were used. Plants grown under water deficiency showed alteration in leaf gas exchange as well as antioxidant activities and reduction of vegetative growth parameters. The plants inoculated with *Bradyrhizobium* strains SEMIA6144 and ESA123 showed increase in vegetative growth parameters, especially those inoculated with *Bradyrhizobium* sp. ESA123 strain obtained from the semi-arid region of Northeast Brazil. At in silico analyzes, ESA123 presented 98.97% similarity with the type strain of *B. kavangense*. The results uncovered beneficial effects of the peanut-*Bradyrhizobium* interaction under water stress condition.

Similarly, the consortium effect of three ACC-deaminase producing rhizobacteria - *Ochrobactrum pseudogrignonense* RJ12, *Pseudomonas* sp. RJ15 and *Bacillus subtilis* RJ46 was evaluated on drought stress alleviation in *Vigna mungo* L. and *Pisum sativum* L (Saikia et al. 2018). Consortium treatment significantly increased seed germination percentage, root length, shoot length and dry weight of treated plants. An elevated synthesis of reactive oxygen species scavenging enzymes and cellular osmolytes, higher leaf chlorophyll content, increase in relative water content and root recovery intension were observed after consortium treatment in comparison with the uninoculated plants under drought conditions. The consortium treatment decreased the ACC accumulation and down-regulated ACC-oxidase gene expression, suggesting that the consortium could be an efficient bio-formulator for crop health improvement in drought affected acidic agricultural fields.

Rhizobial species has also been found to differ in their intrinsic osmotolerance measured by capacity to tolerate and grow under variable concentration of NaCl. *B. japonicum*, *R. etli* and *R. leguminosarum* showed sensitivity to salt by complete growth inhibition at 100 mM NaCl (Boncompagni et al. 1999); whereas growth of *Mesorhizobium huakuii*, *R. tropici* IIB and *S. fredii* inhibited at 200 mM NaCl showing moderate sensitivity, but *S. meliloti* and *A. tumefaciens* found to be highly salt tolerant and grow at 300 mM NaCl (Bernard et al. 1986). *Rhizobium* spp. from nodules of *Acacia*, *Hedysarum*, *Leucaena* and *Prosopis* plants can withstand salt concentration up to 500 mM NaCl (Zhang et al. 1991). Rhizobia tolerate stress because of accumulation osmoprotectants, improved production of exopolysaccharides, ROS-scavenging enzymes and heat shock proteins and chaperons through expression of NaCl-responsive loci (Vriezen et al. 2007). Choudhary and Sindhu (2017) found fifty five rhizobacterial strains from the chickpea rhizosphere soil and selected for their salt tolerance. At 3% NaCl concentration, 41.8% rhizobacterial isolates formed colonies and only 10.9% isolates showed growth at 4% NaCl concentration.

Capacity of rhizobia to tolerate abiotic stresses like heavy metals and pesticides, aids rhizobia to accomplish their advantageous PGP activities in stress environments. Plant responses to various environmental stress is equally dependent on host plant reaction and symbiosis procedure of rhizobial symbiosis (Yang et al. 2010). Grover et al. (2011) revise importance of microorganisms in adaptation of crops to different abiotic stresses. There are widespread reports on tolerance and nodule forming efficiency of *Rhizobium* and *Bradyrhizobium* to soil acidity, salinity, alkalinity, temperature and osmotic stress conditions (Graham 1992; Kulkarni and Nautiyal 2000; Defez et al. 2017). Osmoprotectants, compatible solutes/osmolytes, similarly perform a multiple functions as showed in *S. meliloti* by proline-betaine that helps as both osmoprotectant (under high osmotic stress) and energy source (under low osmotic stress) (Miller-Williams et al. 2006).

Plants being sessile, their growth and yield are strongly influenced by biotic stress. Biotic stress is caused by various pathogens, such as bacteria, viruses, fungi, nematodes, protists and insects. Common impacts of these biotic factors include imbalanced hormonal regulation, nutrient imbalance and physiological disorder results in a substantial decrease in agricultural production (Haggag et al. 2015). Microbial diseases cause malfunction in plants which result in decrease in ability of plant to live and preserve its ecological niche. Plant diseases result either in death or may greatly impair growth and yield of the plant. Pathogenic microorganisms generally deteriorate or extinguish plant tissues and decrease crop production ranging from 25 to 100% (Choudhary and Sindhu 2015). Among the different kind of diseases, root diseases are projected to give 10–15% yield losses globally. Biotic stress also has adverse impacts on plants co-evolution, population dynamics, ecosystem nutrient cycling, natural habitat ecology and horticultural plant health (Gusain et al. 2015). Global crop yields are reduced by 20–40% annually due to pests and diseases (Strange and Scott 2005).

Yadav et al. (2015) obtained 207 strains of *M. ciceri*, from root nodules of chickpea plants and selected for antagonistic influence against *F. oxysporum* f. sp. *ciceri*. Seven strains (MC69, MC84, MC96, MC99, MC180, MC183 and MC190) showed antagonistic effects against *F. oxysporum* f. sp. *ciceri*, but none of them was observed to produce antibiotic or solubilized tricalcium phosphate. Three isolates i.e., MC84, MC96 and MC99 showed siderophore production. MC99 was found to be best antagonistic strain as it manufactured maximum quantity of siderophore.

7.5.4 Bioremediation of Organic Pollutants by Rhizobia

Many free-living rhizobial strains in the genera *Rhizobium*, *Sinorhizobium* and *Bradyrhizobium* showed resistance to polycyclic aromatic hydrocarbon (PAHs), polychlorinated biphenyl (PCBs), aromatic heterocycles (i.e., pyridine) or other toxic organic compounds (Keum et al. 2006; Poonthrigpun et al. 2006; Tu et al. 2011). Ahmad et al. (1997) isolated and characterized a different *R. meliloti* strains from soils polluted with aromatic/chloroaromatic hydrocarbons. Moreover, acenaphthylene and phenanthrene are omnipresent polycyclic hydrocarbons in the environment. *Rhizobium* sp. strain CU-A1 can completely degrade acenaphthylene (600 mg l^{-1}) within three days of inoculation via naphthalene- 1, 8-dicarboxylic acid metabolism pathway (Poonthrigpun et al. 2006). *Sinorhizobium* sp. C4 can consume phenanthrene as a only carbon source and 16 intermediary metabolites engaged in degradation pathway have been recognized (Keum et al. 2006).

Polychlorinated biphenyls are classified as persistent organic pollutants (POPs) varying in the number of chlorine atoms (1–10) bound to their biphenyl rings (Passatore et al. 2014). Tu et al. (2011) reported degradation of more than 70% of 2, 4, 4-TCB (PCB28) by *S. meliloti* ACCC17519. In trials under aerobic conditions, 2- hydroxy-6-oxo-6-phenylhex-2, 4-dienoic acid (HOPDA), the meta cleavage product in typical PCBs-degradative pathway, was recognized as principal intermediate using GC-MS during the biotransformation of 2, 4, 4-TCB by *S. meliloti*. Certain toxic aromatic acids and their hydroaromatic biosynthetic intermediates (i.e., quinate and shikimate) usually disseminated in plants and rhizosphere found to encourage growth of rhizobia (Parke et al. 1985). Mimosine [β-*N*-(3-hydroxy-4-pyrid-one)-amino propionic acid], an aromatic toxin manufactured by the roots of *Leucaena* sp., is toxic to both bacteria and eukaryotic cells (Awaya et al. 2005). Several *Rhizobium* strains forming nodules on *Leucaena* reported to have ability to use mimosine as a source of carbon and nitrogen (Soedarjo et al. 1995; Soedarjo and Borthakur 1998), emphasizing catabolic efficiency of aromatic compounds in rhizobia.

7.5.5 Impacts of Grain Legumes and Rhizobia on Atmosphere and Soil Quality

Inclusion of legumes into agricultural cycles helps in decreasing usage of fertilizers and energy in arable systems and subsequently reducing GHG (greenhouse gases) productions (Reckling et al. 2016). N fertilizer savings across Europe (Reckling et al. 2016), in cycles comprising leguminous crops, range around 277 kg ha^{-1} of CO_2 annually (Jensen et al. 2012). In view of an effectiveness of 2.6–3.7 kg CO_2 produced per kilogram of N synthesized, annual global fertilizer results in emission of 300 Tg of CO_2 into the atmosphere annually (Jensen et al. 2012). Moreover, the CO_2 exhaled from nodule containing roots of leguminous plants derives from atmosphere by photosynthetic activities. On the other hand, all CO_2 released in process of N-fertilizer production comes from fossil energy, thus defining a net influence on atmospheric concentration of CO_2 (Jensen et al. 2012). N_2O accounts for 5–6% of the total atmospheric GHG (Crutzen et al. 2007) and agriculture represents chief source about 60% of mane-made N_2O emissions; (Reay et al. 2012), because of both animal and crop production. A major quantity of these productions derives from use of nitrogenous fertilizers. Application of 100 kg of N fertilizer emits 1.0 kg of N_2O (Jensen et al. 2012) though various quantities of emission rely on number of factors viz. nitrogen application rate, soil organic carbon content, soil pH and texture (Peoples et al. 2009; Rochester 2007). Denitrification reaction is prime source of N_2O in majority of cropping and pasture systems (Peoples et al. 2004; Soussana et al. 2010).

In latest years, numerous experiments focussed on role of legumes to decrease GHG productions. Jeuffroy et al. (2013) proved that legumes produce about 5–7 times less GHG per unit area in comparison to other crops. Measurement of nitrous oxide fluxes showed that peas released 69 kg N_2O ha^{-1} which was far less than winter wheat emitting 368 kg N_2O ha^{-1} and rape producing 534 kg N_2O ha^{-1}. Clune et al. (2017) studied various life cycle assessment (LCA) experiments on GHG production for the period of 2000 to 2015 world over showing Global Warming Potential (GWP) values of pulses was very low (0.50–0.51 kg CO_2 eq kg^{-1} produce or bone-free meat). Schwenke et al. (2015) taken us two field trials in black Vertosol in sub-tropical Australia, showed 385 g N_2O-N ha^{-1} which was significantly higher as compared to emission from chickpea (166 g N_2O-N ha^{-1}), faba bean (166 g N_2O-N ha^{-1}) and field pea (135 g N_2O-N ha^{-1}). Similarly they have also reported that grain legumes showed significantly lower emission factor proving that nitrogen fixed by legumes is less emissive form of nitrogen input as compared to fertilizer nitrogen. However, the key factor determining effect of legumes for reducing greenhouse gas emission governed by management of agro-ecosystems in which they are incorporated. Senbayram et al. (2016) reported that mono cropping of faba bean showed threefold higher collective N_2O release (441 g N_2O ha^{-1}) as compared to unfertilized wheat (152 g N_2O ha^{-1}). On the other hand, intercropping of faba bean with wheat gave 31% less N_2O emissions fluxes as compared to nitrogen fertilized wheat. Nevertheless, benefits obtained by addition of legumes in crop rotations turn out to be noteworthy when market charges of Nitrogenous fertilizer are considered (Jensen et al. 2012).

7.6 Influence of *Rhizobium* Application on Yield of Leguminous Crops

Rhizobium was extensively studied because of its importance in agriculture and environment (Karaman et al. 2013; Nyoki and Ndakidemi 2014). Application of efficient strains of *Rhizobium* showed significant increase in nodulation, nitrogen absorption and crop yield (Thies et al. 1991; Wani et al. 2007a; Franche et al. 2009) (Table 7.4). Elsheikh (1998) inoculation of five guar (*Cyamopsis tetragonoloba*) cultivars, namely, HFG-75, HFG-182, HFG-363, HFG-408 and WB-195 with *Bradyrhizobium* strains TAL 169 and TAL 1371 (introduced) and strains ENRRI 16A and ENRRI 16C (local) significantly enhanced yield, protein, crude fibre and mineral content in guar under field conditions. Indigenous isolates showed higher influence on nodulation and plant growth parameters as compared to exogenous strains. Karasu and Dogan (2009) reported that seed treatment of chick pea (*Cicer arietinum*) seeds with *R. cicero* showed significantly higher seed yield, plant height, first pod height, number of pods per plant, number of seeds per plant, harvest index and 1000 seed weight as compared to treatments receiving various doses of nitrogen through ammonium nitrate (0, 30, 60, 90 and 120 kg ha^{-1}). Native genotype as crop material provided maximum yield (2149.1 kg ha^{-1}) among three chick pea genotypes utilized. Various mixtures of microorganisms utilized looking to the further research needs in this area (Gopalakrishnan et al. 2015). Utilization of appropriate species of microbes as an inoculant in N exhausted environments might be a superior method to increase legume growth and development.

Table 7.4 Growth improvement of various legumes by inoculation of selected *Rhizobium* strains

Rhizobium species	Contributions in growth improvement	References
Bradyrhizobium spp.	Increased nodulation, shoot and root growth in legumes. Enahancing plants' tolerance to drought and synthesis of indole-3-acetic acid	Shaharoona et al. (2007), Uma et al. (2013) and Gopalakrishnan et al. (2015)
Rhizobium strain MRPI	Stimulated nodulation, leghaemoglobin concentration, seed protein and seed harvest in pea plant	Ahemad and Khan (2011)
Rhizobium spp.	Significant increase in height, pod number, length and seed weight of *Vigna mungo* and *Vigna radiate*	Ravikumar (2012)
Rhizobium sp. RL9	Improved development, nitrogen content, seed protein content and seed yield of lentil plant under heavy metal stressed conditions	Wani and Khan (2013)
Sinorhizobium meliloti	Enhanced biomass diversity in black medic plant exposed to copper stress	Gopalakrishnan et al. (2015)
Bradyrhizobium strain S24	Improved nodulation, nitrogen fixation and plant biomass	Sindhu and Dadarwal (1986, 1992, 1995a)
Mesorhizobium strain Ca181	Improved nodulation, nitrogen fixation and shoot dry weight	Sindhu and Dadarwal (2001a) and Goel et al. (2002)

Table 7.5 Inoculation effect of rhizobia exerted against abiotic stress on host plants

Rhizobia	Crop species	Growth condition	Remarks	References
Drought stress				
R. tropici coinoculated with *Paenibacillus polymyxa*	Kidney bean	Greenhouse	Increased plant height, shoot dry weight and nodulation	Figueiredo et al. (2008)
M. mediterraneum LILM10	Chick pea	Field study	Higher nodulation, shoot dry weight and grain yield	Romdhane et al. (2009)
R. elti (engineered for enhanced trehalose-6-phosphate synthase)	Kidney bean	Pot studies	Superior nodulation, nitrogenase activity and biomass yield	Suárez et al. (2008)
Bradyrhizobium sp.	–	*In vitro* and pot culture	Improved drought resistance, IAA and EPS production, nodule numbers, nitrogenase activity in nodules and nitrogen content of nodules	Uma et al. (2013)
Temperature stress				
Acacia rhizobia (40 strains)	–	*In vitro*	Occurrence of small and large plasmids, buildup of free glutamate, three rhizobia strains tolerated 1.4M NaCl	Gal and Choi (2003)
M. ciceri, *M. mediterraneum* and *S. medicae*	Chick pea	Glass house	*M. ciceri* improved nodulation and CAT activity, reduction in nodule protein and SOD activity	Mhadhbi et al. (2004)
M. ciceri ch-191	Salt resistant and sensitive chick pea cultivars	*In vitro*	Reduced plant dry weight and nitrogenase activity in sensitive cultivars, normal nodule weight and shoot K/Na ratio and decreased foliar increase of Na in tolerant cultivars	Tejera et al. (2006)
Rhizobial strains	Lentil	Field study	Increased plant biomass, nodule number and nodule dry weight	Islam et al. (2013)

The response of treatment of various rhizobial species on legumes under various stress conditions depends on the host plant response (Table 7.5), but this response can also be affected by rhizobia and progression of symbiosis (Yang et al. 2010). Grover et al. (2011) has reviewed the job of microbes in adaptation of crops to different abiotic stresses. Moreover, soil acidity, salinity, alkalinity, temperature and osmotic stress conditions have been found to affect the resistance and nodulation capacity of *Rhizobium* and *Bradyrhizobium* in the soil (Graham 1992; Kulkarni and Nautiyal 2000; Defez et al. 2017).

Mfilinge et al. (2014) reported that inoculation of soybean (*Glycine max* L.) with *Rhizobium* showed significant increase in crop growth and yield components viz. number of branches bearing pod per plant, total number of pods per plant and seed number per pods. Seed treatment of *R. leguminosarum* in pea and lentil showed increased pea nodulation, shoot/root diversity and pea seed yield (Bourion et al. 2017). Likewise, seedling height, nodule and shoot biomass of lentil were increased. Bourion et al. (2017) reported increase in nodulation of chickpea by inoculation of *Rhizobium* species with significantly higher plant growth, root dry weight and number of nodules in greenhouse and field. Ravikumar (2012) reported significantly higher plant height, fresh weight, roots, nodules, leaves, shoots and pods number, pod length and seed weight of *Vigna mungo* and *Vigna radiata* inoculated with *Rhizobium* as compared to uninoculated control. Height of soybean plants treated with *Rhizobium* under field conditions was significantly higher and stem girth was also improved in greenhouse and field experiments (Tairo and Ndakidemi 2013). Likewise, Nyoki and Ndakidemi (2014) showed inoculation of cowpea with rhizobial isolates gave significantly higher plant height as compared to control treatment.

7.7 Coinoculation Effect of PGPR with *Rhizobium* Strains

The plant growth promoting effects of *Rhizobium* species are boosted when coinoculated with other microbes (Table 7.6). In coinoculation, some microbes function as assistant to improve the efficiency of the other microorganisms. Therefore, coinoculation of certain bacteria with *Rhizobium* spp. Improve efficiency of the rhizobial spp. Which ultimately results in increased crop productivity. Recently, coinoculation of *Pseudomonas, Enterobacter, Serratia* and *Bacillus* spp. with *Rhizobium/Bradyrhizobium* showed increase in number of nodules, nitrogen fixation and plant biomass of green gram, chickpea and other legumes (Sindhu et al. 1999a, b, 2002a, b; Goel et al. 2000). Therefore, combined inoculation of nitrogen fixing bacteria and PGPR could be explored for enhancing nitrogen fixation in rhizosphere of cereal and legume crops.

Coinoculation of N_2-fixing *A. vinelandii* with *Rhizobium* spp showed increased number of nodules in soybean, pea (*Pisum sativum*) and clover (*Trifolium pratense*) (Burns et al. 1981). Sameway, combined inoculation of *A. brasilense* with *Rhizobium* resulted in higher efficiency in soybean and groundnut (Iruthayathas et al. 1983; Raverkar and Konde 1988). Coinoculation of *Rhizobium* spp. and *Azospirillum* spp. showed increased root hair formation, number of root nodules and flavonoid content in root exudates in comparison to individual application of *Rhizobium* spp. (Itzigsohn et al. 1993, Burdman et al. 1997; Remans et al. 2007, 2008). Efficiency of *Azospirillum* on the legume-*Rhizobium* symbiosis was also observed to be genotype dependent. *Azospirillum* – *Rhizobium* combined inoculation in common bean (*Phaseolus vulgaris* L.) cv. DOR364 showed increase in rate of nitrogen fixation and yield at all sites in field trials (Remans et al. 2008). Coinoculation of *A. lipoferum* and *R. leguminosarum* bv. *trifolli* showed enhanced

Table 7.6 Effect of combined inoculation of rhizobia with rhizobacteria or arbuscular mycorrhizal fungi on legumes

Rhizobia	Coinoculants	Host plant	Proposed mechanism(s)/plant response	References
Rhizobium sp.	*Pseudomonas* sp. LG, *Bacillus* sp. Bx	*Paikiniana vulgaris*	P solubilization, IAA, ammonia and siderophore production	Stajkovic et al. (2011)
R. leguminosarum strain PR1	*Pseudomonas* sp. strain NARs1	*Lens culinaris*	Better growth and nutrient uptake	Mishra et al. (2011)
B. japonicum strains MN-S and TAL-102	AM fungi, *Glomus intraradices*	*Vigna radiata*	Significant increase in plant biomass and N contents	Yasmeen et al. (2012)
R. leguminosarum	PGPR, enriched compost	*Lens culinaris*	ACC deaminase activity of PGPR and symbiotic proficiency of rhizobia	Iqbal et al. (2012)
Rhizobium spp. strain Mg6	PGPR strains A1 and A2	*Phaseolus vulgaris*	ACC deaminase activity	Aamir et al. (2013)
Rhizobium sp. strain PK20	*Pseudomonas* sp. strain M9	*Vigna radiata*	ACC deaminase activity of *Pseudomonas* sp. M9	Ahmad et al. (2011, 2013)
R. leguminosarum	*Pseudomonas* spp.	*Vicia faba*	P solubilization, phytohormone and siderophore production	Saidi et al. (2013)
Mesorhizobium sp. BHURC03	*Pseudomonas aeruginosa* BHUPSB02	*Cicer arietinum*	Increased P and Fe uptake, nodulation as well as IAA synthesis	Verma et al. (2013)
Rhizobium sp.	PGPR, Phosphorus-enriched compost	*Cicer arietinum*	Increased growth and nodulation by ACC deaminase activity	Shahzad et al. (2014)
Rhizobium leguminosarum bv. *viciae*	Arbuscular mycorrhizal fungi	*Vicia faba*	Mobilization of P, Fe, K and other minerals	Abd-Alla et al. (2014)

nodule formation in white clovers (Tchebotar et al. 1998). The mechanisms behind enhanced efficacy was believed to be increase in infection sites for *Rhizobium* spp. by *Azospirillum* which in turn leads to improved nodule formation while application of *Rhizobium* and *Azospirillum* was found to increase siderophore, vitamins and phytohormones biosynthesis (Cassan et al. 2009; Dardanelli et al. 2008). *Azotobacter* came out as a potential coinoculant for *Rhizobium* as it increases vitamins and phytohormones synthesis which ultimately results in increase in nodule formation (Akhtar et al. 2012).

Coinoculation of *R. phaseoli* with *P. putida* showed increased nodulation of beans (*Phaseolus vulgaris*) under greenhouse and field trial conditions but no significant increase in bean yield was observed indicating increase in nodule numbers and *Rhizobium* infection has not direct correlation with crop yield (Grimes and Mount 1984). Bolton et al. (1990) also observed that coinoculation of *Rhizobium* and *Pseudomonas* spp. increases nodulation of pea but no significant difference were observed in shoot dry matter. On the contrary, combined inoculation of rhizobia with other rhizobacteria showed increase in nodule number, root length, plant biomass and yield in various legume crops. For example, Chanway et al. (1989) reported that individual inoculation of nine PGPR strains showed no significant impact on pea growth in field, whereas it gave against significant increase in emergence, vigour, nodule development, nitrogen fixation and root weight in lentil under field conditions. Combined inoculation of these nine strains of PGPR along with *Rhizobium* sp. *cicer* strain Ca181 showed increase in nodule numbers and growth of chickpea with simultaneous reduction of wilt disease (Khot et al. 1996).

Coinoculation of the five strains of fluorescent pseudomonad and *R. leguminosarum* biovar *viciae* enhances shoot and root length as well as dry weight of *Pisum sativum* L. cv. Capella (Dileep Kumar et al. 2001). Goel et al. (2002) reported that coinoculation of chickpea with *Pseudomonas* strains MRS23 and CRP55b, and *Mesorhizobium* sp. *Cicer* strain Ca181 showed 68.2–115.4% increase in nodule numbers at 80 and 100 days after planting, respectively as compared to inoculation of *Mesorhizobium* sp. *Cicer* strain Ca181 alone under sterile conditions. Treatments receiving combined inoculation showed 1.18–1.35 times higher shoot ratio as compared to that of *Mesorhizobium* inoculation and 3.25–4.06 times higher shoot ratio as compared to uninoculated control. Sameway combined inoculation of *B. japonicum* and *P. fluorescens* showed increase in nodule numbers and growth of soybean (Li and Alexander 1988; Nishijima et al. 1988; Dashti et al. 1998), *R. meliloti* with *Pseudomonas* in alfalfa (Li and Alexander 1988; Knight and Langston-Unkefer 1988), *R. leguminosarum* with *P. fluorescens* strain F113 in pea (Andrade et al. 1998) and *Mesorhizobium/Bradyrhizobium* strains with *Pseudomonas* sp. in green gram [*Vigna radiata* (L.) wilczek] and chickpea (Sindhu et al. 1999a, b; Goel et al. 2000, 2002). Fox et al. (2011) reported that coinoculation of *Medicago truncatula* with *Pseudomonas fluorescens* WSM3457 and *Sinorhizobium* showed increase in number of infection sites number of root hairs. Moreover, coinoculation of *P. aeruginosa* and *Mesorhizobium* sp. showed significantly higher shoot and root dry weight, nodule numbers, grain and straw yield as well as phosphorus uptake in chickpea (Verma et al. 2013). Besides growth promotion chickpea plants receiving inoculation of consortium comprising of *A. chroococcum*, *Trichoderma harzianum*, *Mesorhizobium* and *P. aeruginosa* showed antagonistic activities against *Rhizoctonia solani* and *Fusarium oxysporum* (Verma et al. 2014).

Holl et al. (1988) stated that inoculation of *Bacillus* species to seeds or roots changed configuration of rhizosphere which ultimately increase growth and yield of various legumes. For example, Halverson and Handelsman (1991) concluded that under field conditions seed treatment with *B. cereus* UW85 gave 31 to 133% higher nodules than untreated soybeans after 28 and 35 days of planting. In soybean plant grown in sterilized soil-vermiculite mixtures, application of UW85 through seed treatment showed 34 to 61% increase in nodulation at 28 days after planting. It was suggested that UW85 influenced nodule formation afterward planting by encouraging bradyrhizobial colonization or by defeating the termination of colonization process. In another experiment, Turner and Backman (1991) showed that seed treatment of peanut seeds with *B. subtilis* enhance germination and seedling emergence, improved nodulation by *Rhizobium* spp., enriched plant nutrition, decreased incidence of root cankers caused by *Rhizoctonia solani* AG-4 and increased root growth. Srinivasan et al. (1997) reported increase in nodule numbers in *Phaseolus vulgaris* by combined inoculation of *R. etli* strain TAL182 and *B. megaterium* S49 as it increased root hair propagation and lateral root development. Podile (1995) reported increase in nodule numbers, plant dry matter and grain yield of pigeon pea by combined inoculation of *Bacillus* sp. and rhizobia. Similar effects were observed in white clover (Holl et al. 1988). Sindhu et al. (2002a) reported that combined inoculation of *Bacillus* strains with efficient *Bradyrhizobium* strain S24 gave 1.28–3.55 times increase in dry mass at 40 days after sowing. Reports suggest that *Bacillus* strains can increase nodulation and nitrogen fixation at 40 days of plant growth (Mishra et al. 2009; Singh et al. 2011; Stajkovic et al. 2011). Elkoca et al. (2007) also showed increase in root weight and yield of chickpea by coinoculation of *Rhizobium* and *Bacillus* spp. Increase in nitrogen fixation and nodule formation was observed in the pigeon pea plants receiving combined inoculation of *Azospirillum, Bacillus* spp. and *Rhizobium* (Remans et al. 2008; Rajendran et al. 2008) (Table 7.6).

Mishra et al. (2009) showed that coinocualtion of *R. leguminosarum*-PR1 and PGPR *B. thuringiensis*-KR1, obtained from the nodules of *Kudzu* vine (*Pueraria thunbergiana*), promoted plant growth of field pea and lentil (*Lens culinaris* L.) under Jensen's tube, growth pouch and non-sterile soil, respectively. Combined inoculation of *R. leguminosarum*-PR1 and *B. thuringiensis*-KR1 (10^6 cfu. ml^{-1}) showed 85 and 73% increase in nodulation in pea and lentil, respectively as compared to individual treatment of *R. leguminosarum*-PR1. Similarly there was also higher shoot weight, root weight and total biomass was observed in combined inoculation treatments as compared to rhizobial application alone. There was 1.04 to 1.15 times and 1.03 to 1.06 times increase in shoot dry weight of pea and lentil, respectively by combined inoculation of different cell density of *B. thuringiensis*-KR1 as compared to inoculation of *R. leguminosarum*-PR1 alone at 42 days of sowing. Cell population of 10^6 cfu. ml^{-1} was found to be critical as higher cell density displayed inhibitory effects on plant growth and nodulation whereas lower one showed reduced cell retrieval and plant growth. Sameway increased nodule number and biomass yield were obtained upon combined inoculation of *B. japonicum* SB1 and *B. thuringiensis*-KR1 in soybean (Mishra et al. 2009).

Coinoculation of *Rhizobium* and P-solubilizing bacteria improved more plant growth as compared to individual applications (Morel et al. 2012; Walpola and Yoon 2013). Bai et al. (2003) stated that coinoculation of *Bacillus* strains with *B. japonicum* in soybean showed significant increases in nodulation, nodule weight, shoot weight, root weight, total biomass, total nitrogen and grain yield. Tariq et al. (2012) reported improvement in nodulation efficiency and grain yield by combined inoculation of plant growth promoting bacteria with crop specific rhizobia in legumes. Remans et al. (2007) showed *Rhizobium* isolates can effectively nodulate bean plants when coinoculated with phosphate solubilizing bacteria. Barbosa et al. (2007) showed that coinoculation of *Bradyrhizobium* sp. and *Paenibacillus polymyxa* Loutit (L) and *Bacillus* sp. (LBF410) can induce nodulation and increased root dry matter in *Vigna unguiculata*. Sameway, synergistic promotion of nitrogen fixation was observed upon coinoculation of endophytic PGPB and *Rhizobium* species in lentils (Khanna and Sharma 2011; Saini and Khanna 2012). In certain cases, PGPR strain which showed ability to increase efficiency of the *Rhizobium* strains in one legume does not showed same impact with another legume. For instance, *Bacillus* sp. strain CECT450 showed ability to improve nodule formation on common bean upon coinoculation with *R. tropici* CIAT 899, whereas it decreased nodule formation in soybean upon coinoculaion with *B. japonicum* USDA 110 (Camacho et al. 2001). Sameway, Elkoca et al. (2007) showed dual and triple mixtures of PGPR with *Rhizobium* OSU-142 and M-3 displayed no substantial result on common bean yield as compared to single inoculations of these bacteria except for *B. subtilis* strain OSU-142 + *B. megaterium* strain M-3, inoculation. Difference in response of coinoculation displayed necessity to develop suitable blends of rhizobia strain and PGPR for specific sites to improve growth of common bean.

Choudhary and Sindhu (2017) reported that coinoculation of chickpea with ACC deaminase producing *Mesorhizobium* strain MBD26 and rhizobacterial isolate RHD18 produced 59 nodules per plant and showed 112.9% increase in plant dry weight in comparison to untreated plants at 50 days of sowing. In presence of salt, bacterial inoculation displayed 31.2% increase in plant dry weight in comparison to untreated plants under in vitro conditions. At 80 days of sowing, combined inoculation of *Mesorhizobium* isolate MBD26 with rhizobacterial isolate RHD18 showed significant increase in nodule number (78 nodules/plant) and 141.9% increase in shoot dry weight in comparison to uninoculated controls.

7.8 Strategies for Improving N_2 fixation

Research efforts for improving nitrogen fixation ability of various strain of nitrogen fixing free living or symbiotic microorganisms were intensified recently as they could provide an alternative source of chemical fertilizers and thereby reduce our reliance on chemical nitrogenous fertilizers. Selection of appropriate approach for improving nitrogen fixation ability of microbial strains depends largely on state in which microbial strain carry out nitrogen fixation either free-living or symbiotically and genes to be targeted for strain improvement i.e. either nitrogen fixation (*nif, fix*) or nodulation (*nod*, *nol*, *noe*) genes. Till date, efforts to improve nitrogen fixation capacity of symbiotic nitrogen fixers of genus *Rhizobium* and *Bradyrhizobium* were intensively done as they form symbiotic relations with agronomically significant legumes (Shantharam and Mattoo 1997; Schmidt et al. 2017).

Numerous approaches were projected to enhance nitrogen fixation in legume crops either by (i) improvement of nodulation and extending host range by transfer of symbiotic plasmid or cloning of nodulation genes; (ii) enrichment of nitrogen fixation; (iii) breeding of legume cultivars for improved nodulation with efficient strains and (iv) nodulation and nitrogen fixation in non-legume crops. Another methodology used comprises the genetic management of non-legumes to integrate *nif* genes from bacteria (Dixon et al. 1997; Gough et al. 1997) or expansion of host range for symbiosis amongst rhizobia and non-legumes (Trinick and Hadobas 1995; Sindhu and Dadarwal 2001b).

7.8.1 Intensification of Nodulation and Expansion of Host Range

Rhizobium-legume relations are frequently host specific and there exist concept of cross inoculation groups wherein specific *Rhizobium* strain can efficiently colonize specific host plant which make them restricted to colonize narrow range of crops (Brewin 1991). Some particular rhizobia linked with the families *Cicereae*, *Trifolieae* and *Vicieae* have limited host ranges (Broughten and Perret 1999). In other symbiotic relationships, host specificity differs significantly between the symbiontic partners. *A. caulinodans* nodulates only *Sesbania rostrata* and *R. meliloti* nodules found on *Medicago, Melilotus* and *Trigonella* plants, while *Rhizobium* sp. NGR234, nodulates above 137 genera of legumes and non-legumes like *Parasponia andersonii* (Young and Johnston 1989).

In actual field situations, legumes encounter large number of rhizobial strains and there are chances of legume facilitated genetic interchange amongst rhizobia or genetic altercation between rhizobia and other types of rhizosphere bacteria (Osborn 2006). Kinkle et al. (1993) showed that exchange of plasmid among populations of *R. leguminosarum* bv. *viciae* and *B. japonicum* respectively, in non-sterile soil. Souza et al. (1994) provided indication that gene transfer was regular between native soil populations of *R. etli*. Because of genetic recombinations occurring in nature, rearrangements of genetic material between bacteria in soil occurs which ultimately results in evolution of new rhizobial populations dissimilar from that of inoculated one (Sullivan et al. 1995; Vlassak et al. 1996). Many times such genetic manipulations could develop greatly adaptable rhizobial population that will govern nodule development in succeeding years.

7.8.1.1 Transfer of Symbiotic Plasmid

Large number of *Rhizobium* strains own plasmids containing genes influencing nodulation (*nod, nol* and *noe* genes), nitrogen fixation (*nif* and *fix* genes) as well as additional cellular functions (Denarie et al. 1992; Fischer 1994). Symbiotic (*sym*) plasmids of *R. leguminosarum* and *R. meliloti* differ in size from 140 kb to 1500 kb (Beynon et al. 1980; Long 1989). Number and size of these plasmids differs between various strains. Transfer of *sym* plasmid of *R. leguminosarum* to other closely related rhizobia belonging to either bv. *trifolii*, bv. *viciae* or bv. *phaseoli* normally induce development of normal nitrogen-fixing nodules on host plants of donor strains (Beynon et al. 1980; Brewin et al. 1980) but when the *sym* plasmid of *R. leguminosarum* was transferred to distantly related species of *R. meliloti,* the transconjugants induce non-nitrogen fixing root nodules on pea and vetch (Kondorosi et al. 1980; Young and Johnston 1989). Similarly, Kondorosi et al. (1982) also observed that transconjugants of *Lotus* rhizobia or tropical cowpea miscellany rhizobia, carrying the symbiotic megaplasmid pRme41b of *R. meliloti* strain 41, formed white non-nitrogen-fixing nodules on *Medicago sativa*. When the *sym* megaplasmid (pRme41b) of *R. meliloti* was mobilized into *Agrobacterium tumefaciens* by cloning a *mob* region into the *sym* megaplasmid (Kondorosi et al. 1982), the transconjugants were capable to induce ineffective nodule like deformations on alfalfa roots. Introduction of *R. leguminosarum* or *R. trifolii sym* plasmid into *Agrobacterium tumefaciens* conferred the ability to nodulate pea and clover, respectively but the nodules formed were ineffective without formation of bacteroids (Hooykaas et al. 1981, 1982). Djordjevic et al. (1983) showed that transfer of plasmid pBRIAN (encoding clover specific nodulation and nitrogen fixation functions) to *A. tumefaciens* strain ANU109 enabled the strain to nodulate white clovers, whereas the same strain carrying the plasmid pJB5JI (encoding pea-specific nodulation and nitrogen fixation) failed to nodulate peas.

Truchet et al. (1984) mobilized the *sym* megaplasmid of *R. meliloti* strain 2011 into *A. tumefaciens* with the help of plasmid RP4 or PGM142. The consequential transconjugants encouraged root distortions on homologous hosts *Medicago sativa* and *Melilotus alba* but not on the heterologous hosts *Trifolium repens* and *T. pratense*. Cytological interpretations showed that bacteria entered only in shallow layers of host tissue by an uncommon infection progression. Sindhu and Dadarwal (1993) constructed recombinant strains by protoplast fusion between *R.* sp. *Vigna* and *R.* sp. *Cicer* that formed effective nodules on green gram but ineffective pseudonodules on chickpea. These results indicated that infection and nodule commencement genes could be expressed in heterologous rhizobia which leads to expansion of host range but bacteroid formation and formation of efficient nitrogen fixing nodules is challenging to attain.

A cryptic plasmid, pRmeGR4b, reported to affect nodulation capacity and competitiveness in *R. meliloti* GR4 (Sanjuan and Olivares 1989). Mutations in the relevant locus, spanning 5 kb region, delayed nodule formation and also reduced nodulation competitiveness. Nucleotide sequence analysis revealed the occurrence of two neighboring genes, *nfe*1 and *nfe*2 (nodule development proficiency), preceded by a functional σ54 and a NifA-dependent promoter (Soto et al. 1993). The *nfe* genes were not present in four other strains of *R. meliloti* and transfer of *nfe* genes by conjugation in these strains was found to increase nodulation efficiency in two of strains (Sanjuan and Olivares 1991a). Expression of both *nfe*1 and *nfe*2 is perhaps triggered in infection and nodule formation by alteration to microaerobic situations that trigger NifA synthesis. Adding of several replicas of *nif*A from *Klebsiella pneumoniae* correspondingly conferred improved nodulation effectiveness of constructed *R. meliloti* strains (Sanjuan and Olivares 1991b). However, Dillewijn et al. (1998) reported that this observed increase in nodulation was not reliant on plasmid-borne *nif*A activity however it was dependent on sensitivity of non-resistant strains to streptomycin carried over from growth cultures. Rogel et al. (2001) revealed that *Ensifer adhaerens* ATCC 33499, could not form nodules on *Phaseolus vulgaris* (bean) and *Leucaena leucocephala*. Transferring symbiotic plasmid of *R. tropici* CFN299 into *E. adhaerens* enables it to form nitrogen fixing nodules on both hosts. *R. tropici* was carefully chosen as donor as its *sym* plasmids deliberated nitrogen fixing nodule formation ability to *A. tumefaciens* on *Phaseolus vulgaris* and *Leucaena leucocephala* (Martinez et al. 1987). The plasmids “a” and “b” were co-transferred from *R. tropici* CFN299 together with plasmid “c” (carrying *nod-nif* genes) into *A. tumefaciens. A. tumefaciens* recombinant strains comprising three plasmids showed better nodulation and nitrogen fixation as compared to recombinant with only plasmid “c”.

7.8.1.2 Transfer of Cloned Nodulation Genes

Rhizobia possess coordinately regulated operons containing nodulation genes either one on symbiotic plasmids (p*sym*) or one on chromosome. Till date, above 60 diverse nodulation genes were described in various rhizobia (Sindhu and Dadarwal 2001a, b, c; Loh and Stacey 2003; Delamuta et al. 2017). Spaink et al. (1989) created chimeric *nod*D gene, containing 75% of *nod*D1 gene of *R. meliloti* at the 5′ end and 27% of *nod*D gene from *R. leguminosarum* bv. *trifolii*. Its expression in *R. leguminosarum* bv. *trifolii* and *R. meliloti* lead to expansion of host range for nodulation up to tropical legumes *Macroptilium atropurpureum*, *Lablab purpureus* and *Leucaena leucocephala*. Expression of chimeric *nod*D gene in *R. leguminosarum* bv. *trifolii* and *R. leguminosarum* bv. *viciae* similarly lead to substantial escalation of nitrogen fixation rates during symbiosis with *Vicia sativa* and *Trifolium repens*. Bender et al. (1988) moved *nod*D1 gene from *Rhizobium* strain NGR234 to a limited host range *R. leguminosarum* bv. *trifolii* strain and this exchange widened nodulation ability of beneficiaries to new hosts comprising non-legume *Parasponia andersonii*. Point mutations in *nod*D of *R. leguminosarum* bv. *trifolii* showed expansion of host range even to non-legume *Parasponia* (McIver et al. 1989).

The transfer of a 14 kb HindIII fragment on recombinant plasmid pRt032 (carrying *nod*ABC and *nod*D genes from *sym* plasmid of *R. leguminosarum* bv. *trifolii* strain ANU843) to other *Rhizobium* species or to *A. tumefaciens* provide capacity to nodulate clover by recipients (Schofield et al. 1984). The conjugative transfer of 14 kb HindIII fragment on plasmids pRt032 and pRKR9032, to *R. fredii* USDA192 strain, extended the host range of *R. fredii* even to clover (Yamato et al. 1997). Transconjugant strain NA102 and YA101 produce non nitrogen fixing small and whitish nodules on clover. The Nod factors synthesized by the transconjugants in presence of apigenin and genistein flavonoids also varied from those of their receiver strains. Concurrent inoculation of *Glycine max* and *Vigna unguiculata* roots with NodNGR factors and *nod*ABC mutants of strain NGR234 or *B. japonicum* USDA110 enabled bacteria to produce nitrogen fixing nodules on corresponding hosts (Relic et al. 1994). NodNGR factors also enabled entrance of *R. fredii* USDA257 into the roots of non-host *Calopogonium caeruleum* (Relic et al. 1994) and of *nod*ABC mutant of NGR234 into *Macroptilium atropurpureum* (Relic et al. 1993).

The allocation of the host-specific *nod*FEGHPQ genes of *R. meliloti* to strains of *R. leguminosarum* bv. *trifolii* or bv. *viciae* provided capacity of nodule formation on alfalfa (Putnoky and Kondorosi 1986) but intensely repressed nodulation on usual host plants, white clover and vetch, respectively (Debelle et al. 1988; Faucher et al. 1989). Mutations in the *nod*H gene of *R. meliloti* (involved in transfer of sulfate on lipo-oligosaccharide Nod factor) intensely repressed nodulation on common host *Medicago sativa* and directed to hindered nodulation on *Melilotus alba* but provided capacity to nodulate non-host plant, vetch (Faucher et al. 1988; Roche et al. 1991). Mutation in *nod*Q gene also expanded host range of *R. meliloti* to vetch (Schwedock and Long 1992). Transfer of *R. meliloti nod*HPQ genes into *R. leguminosarum* bv. *trifolii* or *R. leguminosarum* bv. *viciae*, none of which owns these genes, indicates production of sulphated Nod signals and prolonged the host range of these strains to alfalfa (Denarie et al. 1996; Long 1996). Mutation of strain NGR234 *noe*E gene (involved in fucose-specific sulfotransferase) obstructed nodulation of *Pachyrhizus tuberosus*, while its overview into closely linked strain USDA257 prolonged host range of *R. fredii* to encompass *Calopogonium caeruleum* (Hanin et al. 1997).

*Nod*L gene is essential for accumulation of an O-acetyl residue at terminal non-reducing glucosamine remainder in *R. meliloti* Nod factors (Ardourel et al. 1994). In strain NGR234, interruption of flavonoid-inducible *nol*L gene results in synthesis of NodNGR factors that lack 3-O- or 4-O- acetate group (Berck et al. 1999). The transconjugants of *R. fredii* strain USDA257 comprising *nol*L of NGR234 formed acetylated Nod factors and nodulated non-hosts *Calopogonium caeruleum*, *L. leucocephala* and *L. halophilus*. Acetylation of Nod factors' fucose of *R. etli* similarly deliberated effective nodulation on some *P. vulgaris* cultivars and on different host *Vigna umbellata* (Corvera et al. 1999). *Nod*Z gene, encodes a fucosyltransferase, which is essential for nodulation of legume siratro by *B. japonicum*, but alteration in *nod*Z of *B. japonicum* does not affect nodulation in soybeans considerably (Nieuwkoop et al. 1987; Stacey et al. 1994). $NodZ^-$ mutants of NGR234 vanished the ability to nodulate *Pachyrhizus tuberosus* (Quesada-Vincens et al. 1997). Allocation of *nod*Z gene to *R. leguminosarum* bv. *viciae* lead to in synthesis of fucosylated Nod signals and widen host range to comprise *Macroptillium* (Lopez-Lara et al. 1996). Inactivation of gene *nod*S, involved in methylation of Nod factors of *A. caulinodans*, NGR234 and *R. tropici* eliminated nodulation of *Leucaena leucocephala* and *Phaseolus vulgaris* (Lewin et al. 1990; Waelkens et al. 1995). Transfer of either *nod*S or *nod*U gene into *R. fredii* USDA257 expanded host range to include *Leucaena* spp. (Krishnan et al. 1992; Jabbouri et al. 1995). These outcomes shown that numerous replacements or alterations at reducing or non-reducing terminus of Nod factors could broaden the host range.

Castillo et al. (1999) utilized precise DNA amplification (SDA) approach to create *S. meliloti* strains CFNM101 and CFNM103, that demarcated 2.5 to 3 copies of symbiotic region (containing *nod*D1, *nod*ABC and *nif*N of p*sym* plasmid). Application of these strains to alfalfa created escalation in nodulation, nitrogen fixation and growth of alfalfa plants in environmentally controlled situations. Likewise, Mavingui et al. (1997) employed random DNA amplification (RDA) in symbiotic plasmid of *R. tropici* to get strains with improved competency for nodulation.

7.8.2 Improvement of Nitrogen Fixation

Structural or regulatory *nif* genes of the nitrogenase enzyme complex can be altered to enhance efficiency of nitrogen fixation. It was proposed that increasing *Nif*A construction, which is the transcriptional activator of other *nif* genes, could improve expression of entire N_2-fixing system (Szeto et al. 1990). Initially greenhouse experiments showed that certain *R. meliloti* strains with higher *nif*A gene expression exhibited a 7–15% rise in alfalfa plant biomass in comparison to parents (Williams et al. 1990). Meanwhile regulatory stage in nitrogen fixation appears to be process of attaching reduced dinitrogenase reductase (Fe-protein, the *nif*H gene product) to dinitrogenase (MoFe-protein) followed by one electron transfer. It was observed that increase in copy numbers of *nif*H gene and its products result in increase in throughput rate of nitrogenase which seems to be reason for occurrence of more than one copy of the *nif*H gene in certain diazotrophs such as *A. vinelandii* (Jacobson et al. 1986), *Rhizobium phaseoli* (Quinto et al. 1985) and *A. sesbaniae* (Norel and Elmerich 1987).

Alteration in expression of the C4- dicarboxylate transport (*dct*) genes could increase substrate transport which in turn increase nitrogen fixation efficiency (Ronson et al. 1990). Root nodules contains photosynthetic energy and utilize roughly 10% of the plant's net photosynthates for nitrogen fixation. Therefore, nitrogen fixation in the *Rhizobium*-legume symbiosis is supposed to be partial by amount of plant-derived photosynthetic outputs accessible to bacteroids (Hardy and Havelka 1975; Sindhu et al. 2003). Birkenhead et al. (1988) proposed that increasing efficiency of endosymbiont to use photosynthate in nodule may results in improved nitrogen fixation rates. Recombinant strains of *R. meliloti* and *B. japonicum* with better expression of *dct*A (structural gene for dicarboxylate transport) and *nif*A genes exhibited 15% escalation in nitrogen fixation rates (Ronson et al. 1990).

Certain nitrogen fixing bacteria like *Rhizobium*, *Azotobacter, Azospirillum* etc. found to increase efficacy of nitrogen fixation by oxidizing hydrogen by means of hydrogenase enzyme, that concurrently formed and developed during nitrogen fixation (Sindhu et al. 1994; Garg et al. 1985). This oxidation of hydrogen enhance ATP biosynthesis. Improved nitrogen fixation efficiency described in nodules and bacteroids of soybean, pea and *Vigna* group of hosts designed by application of Hup^+ strains (Emerich et al. 1979; Dadarwal et al. 1985; Evans et al. 1987). Improved hydrogenase activity in root nodule bacteroids showed increase in soybean yield by use of near isogenic strains of *B. japonicum* (Hanus et al. 1981; Hungaria et al. 1989). Second strategy to increase yields could be to increase the activity of the hydrogenase in bacterial strains that previously own it. Mutants of Hup^+ *B. japonicum* strains (Merberg and Maier 1983) or *Rhizobium* sp. strains (Sindhu and Dadarwal 1992) were developed with enhanced hydrogenase activity. Inocualtion of mutants of *Rhizobium* sp. strains showed higher in dry matter yield of green gram and black gram. The *hup* genes, coding biosynthesis of uptake hydrogenase was cloned and utilized to transform Hup^- strains. These Hup^+ recombinants exhibited increased nitrogen fixation (Pau 1991).

7.8.3 Breeding for Enhanced Nodulation

Changing the genetic make-up of plants to influence both endophytic and external populations suggest likelihood of creating favorite rhizosphere communities (O'Connell et al. 1996; Sindhu et al. 2018). Plant breeding strategy could be used to combine preference traits from several sources to generate plant genotypes capable of excluding nodulation by ineffective indigenous rhizobia. Hardarson et al. (1982) showed that the selection of alfalfa for physiological and morphological traits associated with nitrogen fixation capability altered the preference of the host plant for effective strains of *R. meliloti*. Nutman (1984) reported that red clover bred for improved nitrogen fixation maintained its superiority against a range of *R. leguminosarum* bv. *trifolii* strains. These studies illustrated the potential for developing broad-spectrum effectiveness for genetically diverse indigenous rhizobia in some legume species. Mytton et al. (1984) assessed genetic variation in nitrogen fixation in different cultivars of *M. sativa* inoculated with diverse strains of *R. meliloti*; one of these cultivars was found relatively insensitive to changes in *Rhizobium* genotype and maintained high average yield.

The specific compatibility between *nod*X of *R. leguminosarum* bv. *viciae* strain TOM and *sym*2 of *Pisum sativum* cv. Afghanistan could be utilized to avoid native rhizobia from nodulating and to permit inoculated strains to nodulate. The *sym*2 gene has already been crossed into a desirable pea cultivar (Trapper) and *nod*X was transferred in effective N_2-fixing *Rhizobium* strain. Performance of these manipulated host cultivar and rhizobial strains appeared promising enough under field studies (Fobert et al. 1991). A similar combined approach involving alteration of both soybean host and *Bradyrhizobium* strains has also been carried out to improve symbiotic N_2 fixation in soybean-*B. japonicum* symbiosis (Cregan et al. 1989; Sadowsky et al. 1991). This strategy involves use of soybean genotypes that restrict the nodulation of indigenous competitive strains and allow nodulation only with desired added strains (Sadowsky et al. 1995). In this way, improved strains produced by genetic engineering or other techniques can be targeted to specifically improve soybean varieties. Thus development of legume cultivars with broad-spectrum effectiveness for genetically diverse indigenous rhizobia could be an alternative beneficial plant breeding strategy to obviate the requirement for legume inoculation (Brockwell and Bottomley 1995). This requires an understanding of the genetics of host and rhizobia, and offers real promise for genetically well-defined systems such as alfalfa and soybean.

Alternative approach of improving number of nodules by alteration of host genome is also utilized to increase nitrogen fixation ability in symbiotic microbes. Proposed strategy is based on hypothesis that nodule formation in legume is suboptimal and obviously increase in nodule numbers results into increased rate of nitrogen fixation. Hypernodulating mutants of soybean developed 100 times more nodules as compared to parent plant (Carroll et al. 1985; Betts and Herridge 1987). Scientists have isolated number of soybean mutants with the higher nodulation efficiency even in presence of nitrate (Carroll et al. 1985) which can produce 3–40 times higher number of nodules as compared to parent crop and demonstrated improved nitrogen fixation capacity (Hansen et al. 1989). Unluckily, these mutants were found to be poor agronomic performers (Pracht et al. 1994) due to fact that plant used up large extent of energy in hosting root nodules and thereby restricting energy required for the nitrogen fixation (Kennedy et al. 1997). Sato et al. (1999) altered source-sink association in hypernodulating soybeans by reducing infection dose so that nodulation is optimized to standard level and resolved that autoregulatory control may play crucial role in improving the number of nodules in soybeans and total nitrogen fixation activity.

7.8.4 Nodulation and Nitrogen Fixation in Nonlegume Hosts

Certain non-legume plants are able to establish nitrogen-fixing symbiosis. The *Frankia* are of great importance which nodulates woody angiosperms like *Alnus* or *Casuarina*. These nodules have simple, branched structures; indicative of solidified lateral roots, however their capability to fix nitrogen is comparable to that in legumes (Clawson et al. 1998). Likewise, non-legume nodulation and nitrogen fixation was seen with *Bradyrhizobium* application in *Parasponia* (Trinick and Hadobas 1995; Webster et al. 1995) with high capacity of nitrogen fixation and structurally related to actinorhizal nodules.

*Nod*D gene of rhizobia proved to regulate the initial level of host specificity (Denarie et al. 1992). Transfer of *nod*D1 gene from NGR234 into *R. leguminosarum* bv. *trifolii* expanded host range to nodulate non-legume *Parasponia andersonii* (Bender et al. 1988). Plasmids containing *nod*DABC genes of *R. leguminosarum* bv. *trifolii* were reassigned to *A. tumefaciens, P. aeruginosa, Lignobacter* sp., *A. brasilense, E. coli* and different non-nodulating mutant rhizobia (owning *sym* plasmid deletions) which enabled them to perform root hair curling and alterations on clover and large number of other non-host legumes (Plazinski et al. 1994), proposing manifestation of *nod*DABC genes in varied array of soil bacteria may spread or effect normal growth of plant root hairs of a varied kind of host and non-host legumes. Attempts to enhance nitrogen fixation by modification of macrosymbiont host plant have been done with leguminous crops such as soybean and alfalfa. In recent times, two model legumes *Medicago truncatula* and *Lotus japonicus* are identified for genetic examination of nodule formation and operational facts of root nodules, by which transgenics can usually be produced. These legumes will perform as tools for the identification and genetic characterization of plant genes engaged in nodule development as well as provides idea about mechanisms controlling root nodule formation.

Present studies to transfer the nitrogen fixation capability to nonleguminous plants showed nodule like structures could be formed on rice and wheat roots with *Rhizobium* strains in artificial conditions by means of hormones or cell wall degrading enzymes (Al-Mallah et al. 1989; Cocking et al. 1994). A precise investigation of these nodule-like structures shown accumulation of bacteria at the spot of lateral root formation and get enter through cracks. *Rhizobium* strains obtained from *Aeschynomene indica* (strain ORS310) and *Sesbania rostrata* (strain ORS571) were observed to produce nodule like structures on developing secondary roots of rice, wheat and maize (Cocking et al. 1994) and displayed considerable nitrogen fixation activity. Wheat plants inoculated with *A. caulinodans* showed higher nitrogen fixation activity whereas uninoculated plants as well as those inoculated with *nif*$^-$ strain of *A. caulinodans* showed absence of nitrogen fixation (Sabry et al. 1997). *A. caulinodans* strain ORS571 having *lac*Z reporter gene was found to be present in cracks of developing lateral roots in rice and wheat (Webster et al. 1997). Sameway, *lac*Z containing *A. caulinodans* strain ORS571 could enter *Arabidopsis thaliana* roots through cracks developed during lateral root formation. The flavonoids, naringenin and diadzein at low concentration considerably roused incidence of lateral root cracks and intercellular colonization of *A. thaliana* roots by *A. caulinodans.*

Tchan and Kennedy (1989) reveled induction of 'para nodules' on wheat by application of 2, 4-dichlorophenoxyacetic acid (2, 4-D) or with auxins IAA and NAA (Naphthyl-acetic acid), along with inoculation of rhizobia or *Azospirillum*. Rolfe and Bender (1991) demonstrated formation of paranodules on rice roots by inoculation of *Rhizobium* having *nod*D allele whose gene product interacts with rice root exudate but could not display nitrogenase activity. It was discussed that transformation of rice may induce new genes and thereby provides great chance to examine the probability for nitrogen fixation in rice. In addition, certain early nodulin homologous genes in legumes were detected in rice genome which is yet to be studied in depth.

In depth research understanding about different physiological and genetic processes in legume plants and bacteria as well as detection of key characters for nodulation in legumes might provide opportunity to enable nonlegumes like rice and wheat to be engaged in symbiosis with nitrogen fixing bacteria (Kennedy and Tchan 1992). Consequently, widespread fundamental studies are required to realize relations between *Rhizobium* and cereal plants with specific weightage on signal exchange mechanisms. Additionally, these altered nodule like structures on lateral roots of cereals must develop microaerobic environment for protection of oxygen sensitive nitrogenase. To develop oxygen protection mechanism, plant could be engineered to accumulate polysaccharides or other O_2 eliminating material within intercellular space upon infection. Plentiful efforts and management are needed in genetics, molecular biology and developmental biology to attain a comprehensive understanding of the *Rhizobium* legume symbiosis and to discover future opportunities for attaining final objective of expressing active nitrogenase in cereal crops (Dixon et al. 1997; Shantharam and Mattoo 1997).

7.9 *Rhizobium* Based Commercially Available Inoculants

Strategies to improve crop production by inoculating plant growth promoting bacteria is accelerated as developing technology because of their environment friendly potentials. Bioinoculants like biofertilizers has been popularized since many years to get advantage positive effects of various soil microbes to boost plant growth and yields. Biofertilizers are microbial inoculants comprising of microbial strains having capacity of nitrogen fixation, phosphate solubilization/mineralization, phytohormone production and biocontrol activities. Rhizobial strains generally utilized as biofertilizers (singly or in mixture) contain a number of genera: *Allorhizobium*, *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Rhizobium* and *Sinorhizobium* (Table 7.7). Prime focus points for development of rhizobial biofertilizer technology are development of appropriate formulation with suitable carrier and adoption of appropriate application methods. Rhizobia-based inoculants generally used for improvement of growth and yield of leguminous crops, whereas *Azotobacter* and *Azospirillum* for enhancement of cereal growth. On contrary *Bacillus* and *Pseudomonas* are utilized as biocontrol agents (as biopesticides) against plant diseases (Fravel 2005; Bravo et al. 2011). Table 7.7 displays certain selected

Table 7.7 Marketed *Rhizobium*-based biofertilizers

Bacteria	Product	Company
Rhizobia	VAULT® HP plus INTEGRAL®	Becker Underwood Corporate, USA
Delftia acidovorans and *Bradyrhizobium*	BioBoost	Brett Young Seeds Ltd., Canada
Rhizobium sp.	SeedQuest®	Soygro (Pty) Ltd., South Africa
Rhizobium sp.	Legumefix	Legume Technology Ltd., UK
Bacillus subtilis and *Bradyrhizobium japonicum*	HiStick N/T, Turbo-N	Becker Underwood Corporate, USA
B. subtilis and *B. japonicum*	Patrol N/T	United Agri Products (UAP) Inc., Canada
Burkholderia cepacia type Wisconsin	Deny	Market VI LLC, Vern Illum 6613 Naskins Shawnee KS 66216, USA
Rhizobium spp.	*Fasloon Ka Jarasimi Teeka*	AARI, Faisalabad, Pakistan
Rhizobium spp.	BioPower	NIBGE, Faisalabad, Pakistan
Rhizobium spp.	Biozote	NARC, Islamabad, Pakistan
Rhizobium spp. and PGPR	Rhizogold	ISES, UAF, Faisalabad, Pakistan
Bradyrhizobium spp. *Mesorhizobium* sp. *ciceri* and PGPR	Rhizoteeka, Azoteeka and phosphoteeka	CCS Haryana Agricultural University, Hisar, India

commercially existing rhizobial inoculants with their producers/trade name. The development of mass production technology for commercial manufacturing of microbial inoculants like biofertilizers is the key point to be considered for spreading wide use of biofertilizers.

7.10 Performance and Limitations of Inoculant Strains

Rhizobial inoculation in soil have showed colonization of soil as well as plant roots to a extent adequately high for proposed aim. In majority of the cases expected effect of biofertilizers inoculation is not witnessed under field conditions in legume or cereal plants and frequently fails to increase crop yield (van Elsas and Heijnen 1990; Akkermans 1994). Regulating factors for performance of microbial strains under field conditions includes abiotic soil factors such as texture, pH, temperature, moisture content and substrate accessibility which should be determined crucially as they showed great influence on survival and activity of inoculated microorganisms (Hegazi et al. 1979; Sindhu and Lakshminarayana 1982; van Veen et al. 1997; Hansena et al. 2018). Efficiency of inoculated nitrogen fixing bacterial strain is determined by genetic and physiological efficiency of bacterial strain (Brockwell et al. 1995). Insertion of genetic markers viz. antibiotic resistance genes or other metabolic markers could assist to mark out introduced strains, whether it is rhizobia, cyanobacteria, azotobacter or azospirilla (Wilson et al. 1995).

A main factor limiting feat of rhizobial inoculants is its inability to survive under competitive stress with the native strains for nodulation (Sindhu and Dadarwal 2000; Sindhu et al. 2003). Rhizobia produces bacteriocins which can inhibit growth of and nodulation by the native ineffective strains (Goel et al. 1999; Sindhu and Dadarwal 2000). Transfer and expression of genes involved in trifolitoxin synthesis i.e. *tfx* genes in rhizobia resulted in to constant synthesis of trifolitoxin and controlled nodulation by indigenous trifolitoxin-sensitive strains on many leguminous crops (Triplett 1988, 1990). Though, efforts to manipulate some rhizobial genes in particular legume rhizosphere places for improving competence failed to show notable results (Nambiar et al. 1990; Sitrit et al. 1993; Krishnan et al. 1999).

Biotechnological methods for improving nitrogen fixation and crop production having narrow utility in field conditions. For example, recombinant strain of *R. meliloti* and *B. japonicum* showed higher expression of *nif*A and *dct*A genes indicating intensification in rate of N_2 fixation but in field conditions, recombinant strains didn't performed well for nitrogen fixation or yield enhancement (Ronson et al. 1990). Alteration of nodulation genes to increase bacterial competence generally resulted in either no nodulation, delayed nodulation or inefficient nodulation (Devine and Kuykendall 1996). Mendoza et al. (1995) improved NH_4^+ assimilating enzymes in *R. etli* by adding an extra copy of glutamate dehydrogenase (GDH), ultimately showed retardation of nodulation on bean plants. Such inhibitory effect was minimized by *Nif*A and thereby postponing the inception of GDH activity after nodule formation (Mendoza et al. 1998). In the same way, efforts to manipulate hydrogen uptake (Hup^+) ability by cloning hydrogenase genes into Hup^- strains of *Rhizobium* showed success only in parts where soybeans are cultivated under restricted photosynthetic energy (Evans et al. 1987). Efforts to construct self-fertilizing crops for nitrogen was also disappointment due to complex nature of nitrogenase enzyme system under unavailability of oxygen safeguard system in eukaryotes (Dixon et al. 1997). Stimulation of nodule formation (pseudonodules) in wheat and rice crops by lytic enzyme of hormonal treatment displayed nitrogenase activity and nitrogen integration in plants. However, the activity expressed is >1% of the significance seen in legumes (Cocking et al. 1994).

7.11 Conclusion

Biological nitrogen fixation provides nitrogen to leguminous crops and hence considered to be significant process for improving yield. Symbiotic nitrogen fixing systems like rhizobia and legumes can fix significant quantity of nitrogen by acclimatizing with varied ecological conditions. So that, influence of rhizobia on legumes cannot be ascertained exactly under harsh environment and there is need to isolate stress tolerant rhizobial strains to act under stress in soil ecosystem which in turn ensures survival and growth of inoculated legumes in challenging soil. We are enriched with the research about molecular mechanism of nitrogen fixation but it is yet to be involved in applied aspects under field studies. As a way out of issue regarding establishment of microbes after inoculation, diazotrophic inoculants should be chosen from native ecological boundaries and re-inoculated in similar environment for ensuring anticipated benefits. Forthcoming research should concentrate on unveiling in situ physiology of inoculant and means to manipulate the same. On applied side, idea development of mixed inoculum with ecologically different strains having same roles should be tested as an alternative of monoculture. The coinoculation of diazotrophic bacteria with rhizosphere bacteria or the inoculation of microbial consortia is preferable because these microorganisms might express beneficial functions more frequently in a soil or rhizosphere system, even under ecologically diverse and/or variable circumstances. Hence, both customary and biotechnological methodologies can be used to improve nitrogen fixation efficiency and crop production in sustainable agriculture.

In general, inoculative application of *Rhizobium* provide 10–15% yield increase in leguminous crops. On the other hand, anticipated effect of biofertilizer application on legumes is generally not attained in field conditions. Commercial inoculants generally fails under field condition because of incompetence to strive with the native, ineffective microbes, which offers a competitive obstruction to inoculated strains. Efforts to operate some rhizobial genes in particular legume rhizosphere environment to improve survival under competitive stress were not successful up to mark. This chapter emphasize potential of plant growth promoting rhizobia for sustainable agriculture as well as highlighted exceptional characteristics to cope up with various biotic and abiotic stresses on a various agricultural crops. Thus, development of broad knowledge on screening approaches and concentrated selection of superlative *Rhizobium* strains for rhizosphere competence and survival is required to improve field efficiency of applied strains. Characterization of such prospective rhizobial strains and evolving a strong technology for farmers is still in developing phase. Current developments of 'omics' technologies provided prospects to exploit genomic, transcriptomic, proteomic and metabolomic means to alter the characters of 'biological designers' to maximize their plant growth promotion proficiency. Bioengineering could possibly be used to operate the tolerance, accumulation and degradation potentials of plants and microbes against pollutants.

References

Aamir M, Aslam A, Khan MY, Jamshaid MU, Ahmad M, Asghar HN, Zahir ZA (2013) Coinoculation with *Rhizobium* and plant growth promoting rhizobacteria (PGPR) for inducing salinity tolerance in mung bean under field condition of semi-arid climate. Asian J Agric Biol 1:17–22

Abd-Alla MH (1994a) Solubilization of rock phosphates by *Rhizobium* and *Bradyrhizobium*. Folia Microbiol 39:53–56

Abd-Alla MH (1994b) Use of organic phosphorus by *Rhizobium leguminosarum* biovar *viciae* phosphatases. Biol Fertil Soils 18:216–218

Abd-Alla MH, El-Enany AWE, Nafady NA, Khalaf DM, Morsy FM (2014) Synergistic interaction of *Rhizobium leguminosarum* bv. *viciae* and arbuscular mycorrhizal fungi as a plant growth promoting biofertilizers for faba bean (*Vicia faba* L.) in alkaline soil. Microbiol Res 169:49–58

Ahemad M, Khan MS (2009a) Toxicity assessment of herbicides quizalafop-p-ethyl and clodinafop towards Rhizobium pea symbiosis. Bull Environ Contam Toxicol 82:761–766

Ahemad M, Khan MS (2009b) Effect of insecticide-tolerant and plant growth promoting Mesorhizobium on the performance of chickpea grown in insecticide stressed alluvial soils. J Crop Sci Biotech 12:217–226

Ahemad M, Khan MS (2011) Insecticide-tolerant and plant growth promoting *Bradyrhizobium* sp. (Vigna) improves the growth and yield of green gram [*Vigna radiata* (L.) Wilczek] in insecticide stressed soils. Symbiosis 54:17–27

Ahemad M, Khan MS (2012a) Ecological assessment of biotoxicity of pesticides towards plant growth promoting activities of pea (*Pisum sativum*)-specific *Rhizobium* sp. strain MRP1. Emirates J Food Agric 24:334–343

Ahemad M, Khan MS (2012b) Productivity of green gram in tebuconazole-stressed soil by using a tolerant and plant growth promoting *Bradyrhizobium* sp. MRM6 strain. Acta Physiol Plant 34:245–254

Ahemad M, Khan MS (2012c) Effects of pesticides on plant growth promoting traits of *Mesorhizobium* strain MRC4. J Saudi Soc Agric Sci 11:63–71

Ahmad D, Mehmannavaz R, Damaj M (1997) Isolation and characterization of symbiotic N_2-fixing *Rhizobium meliloti* from soils contaminated with aromatic and chloroaromatic hydrocarbons: PAHs and PCBs. Int Biodeter Biodegr 39:33–43. https://doi.org/10.1016/S0964-8305(96)00065-0

Ahmad F, Ahmad I, Khan MS (2008) Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. Microbiol Res 163:173–181

Ahmad M, Zahir ZA, Asghar HN, Asghar M (2011) Inducing salt tolerance in mung bean through coinoculation with rhizobia and plant-growth-promoting rhizobacteria containing 1-aminocyclopropane-1- carboxylate-deaminase. Can J Microbiol 57:578–589

Ahmad M, Zahir ZA, Khalid M, Nazli F, Arshad M (2013) Efficacy of *Rhizobium* and *Pseudomonas* strains to improve physiology, ionic balance and quality of mung bean under salt-affected conditions on farmer's fields. Plant Physiol Biochem 63:170–176

Akhtar N, Qureshi MA, Iqbal A, Ahmad MJ, Khan KH (2012) Influence of *Azotobacter* and IAA on symbiotic performance of *Rhizobium* and yield parameters of lentil. J Agric Res 50:361–372

Akkermans ADL (1994) Application of bacteria in soils: problems and pitfalls. FEMS Microbiol Rev 15:185–194

Alexandre A, Oliveira S (2011) Most heat-tolerant rhizobia show high induction of major chaperone genes upon stress. FEMS Microbiol Ecol 75:28–36

Al-Mallah MK, Davey MR, Cocking EC (1989) Formation of nodular structures on rice seedlings by rhizobia. J Expt Bot 40:473–478

Andrade G, De Leij FAAM, Lynch JM (1998) Plant mediated interactions between *Pseudomonas fluorescens*, *Rhizobium leguminosarum* and arbuscular mycorrhizae on pea. Lett Appl Microbiol 26:311–316

Antoun H, Beauchamp CJ, Goussard N, Chabot R, Lalande R (1998) Potential of *Rhizobium* and *Bradyrhizobium* species as plant growth promoting rhizobacteria on non-legumes: effect on radishes (*Raphanus sativus* L.). Plant Soil 204:57–68

Appelbaum E (2018) The *Rhizobium*/*Bradyrhizobium*-legume symbiosis. In: Molecular biology of symbiotic nitrogen fixation. CRC Press, Boca Raton, pp 131–158

Ardourel M, Demont N, Debelle F, Maillet F, de Billy F, Prome JC, Denarie J, Truchet G (1994) *Rhizobium meliloti* lipo-oligosaccharide nodulation factors: different structural requirements for bacterial entry into target root hair cells and induction of plant symbiotic development responses. Plant Cell 6:1357–1374

Arora NK, Kang SC, Maheshwari DK (2001) Isolation of siderophore producing strains of *Rhizobium meliloti* and their biocontrol potential against *Macrophomina phaseolina* that causes charcoal rot of groundnut. Curr Sci 81:673–677

Arshad M, Shaharoona B, Mahmood T (2008) Inoculation with *Pseudomonas* spp. containing ACC-deaminase partially eliminates the effects of drought stress on growth, yield and ripening of pea (*Pisum sativum* L.). Pedosphere 18:611–620

Ashraf M, Akram NA (2009) Improving salinity tolerance of plants through conventional breeding and improving salinity tolerance of plants through conventional breeding and genetic engineering: an analytical comparison. Biotechnol Adv 27:744–752

Awaya JD, Fox PM, Borthakur D (2005) *pyd* Genes of *Rhizobium* sp. strain TAL1145 are required for degradation of 3-hydroxy-4-pyridone, an aromatic intermediate in mimosine metabolism. J Bacteriol 187:4480–4487. https://doi.org/10.1128/JB.187.13.4480-4487.2005

Bai Y, Zhou X, Smith DL (2003) Enhanced soybean plant growth resulting from coinoculation of *Bacillus* strains with *Bradyrhizobium japonicum*. Crop Sci 43(5):1774–1781

Bajguz A, Tretyn A (2003) The chemical characteristic and distribution of brassinosteroids in plants. Phytochemistry 62:1027–1046

Barbosa JA, Silva LP, Teles RC, Esteves GF, Azevedo RB, Ventura MM, de Freitas SM (2007) Crystal structure of the Bowman-Birk inhibitor from *Vigna unguiculata* seeds in complex with β-Trypsin at 1.55 Å resolution and its structural properties in association with proteinases. Biophysical J 92(5):1638–1650

Barbosa DD, Brito SL, Fernandes PD, Fernandes-Junior PI, Lima LM (2018) Can *Bradyrhizobium* strains inoculation reduce water deficit effects on peanuts? World J Microbiol Biotechnol 34:87. https://doi.org/10.1007/s11274-018-2474-z

Barrios S, Ouattara B, Strobl E (2008) The impact of climatic change on agricultural production: is it different for Africa? Food Policy 33(4):287–298

Bender GL, Nayudu M, Le Strange KK, Rolfe BG (1988) The *nod*DI gene of *Rhizobium* strain NGR234 is a key determinant in the extension of host range to non-legume *Parasponia*. Mol Plant Microbe Interact 1:254–256

Berck S, Perret X, Quesada-Vincens D, Prome JC, Broughten WJ, Jabbouri S (1999) NolL of *Rhizobium* sp. NGR234 is required for O-acetyltransferase activity. J Bacteriol 181:957–964

Bernard T, Pocard JA, Perroud B, Le Rudulier D (1986) Variations in the response of salt-stressed *Rhizobium* strains to betaines. Arch Microbiol 143:359–364

Berraho EL, Lesueur D, Diem HG, Sasson A (1997) Iron requirement and siderophore production in *Rhizobium ciceri* during growth on an iron-deficient medium. World J Microbiol Biotechnol 13:501–510

Betts JH, Herridge DF (1987) Isolation of soybean lines capable of nodulation and nitrogen fixation under high levels of nitrate supply. Crop Sci 27:1156–1161

Beynon JL, Beringer JE, Johnston AWB (1980) Plasmids and host range in *Rhizobium leguminosarum* and *Rhizobium phaseoli*. J Gen Microbiol 120:421–429

Bhagat D, Sharma P, Sirari A, Kumawat KC (2014) Screening of *Mesorhizobium* spp. for control of Fusarium wilt in chickpea in vitro conditions. Int J Curr Microbiol Appl Sci 3:923–930

Birkenhead K, Manian SS, O'Gara F (1988) Dicarboxylic acid transport in *Bradyrhizobium japonicum*: use of *Rhizobium meliloti dct* gene(s) to enhance nitrogen fixation. J Bacteriol 170:184–189

Biswas J, Ladha J, Dazzo F (2000) Rhizobia inoculation improves nutrient uptake and growth of lowland rice. Soil Sci Soc Am J 64:1644–1650

Bockman OC (1997) Fertilizers and biological nitrogen fixation as sources of plant nutrients: perspectives for future agriculture. Plant Soil 194:11–14

Bohlool BB, Ladha JK, Garrity DP, George T (1992) Biological nitrogen fixation for sustainable agriculture: a perspective. Plant Soil 141(1-2):1–11

Boiero L, Perrig D, Masciarelli O, Penna C, Cassán F, Luna V (2007) Phytohormone production by three strains of *Bradyrhizobium japonicum* and possible physiological and technological implications. Appl Microbiol Biotechnol 74:874–880

Bolton H Jr, Elliott LF, Turco RF, Kennedy AC (1990) Rhizoplane colonization of pea seedlings by *Rhizobium leguminosarum* and deleterious root colonizing *Pseudomonas* sp. and effects on plant growth. Plant Soil 123:121–124

Boncompagni E, Osterås M, Poggi MC, Le Rudulier D (1999) Occurrence of choline and glycine betaine uptake and metabolism in the family rhizobiaceae and their roles in osmoprotection. Appl Environ Microbiol 65:2072–2077

Bourion V, Heulin-Gotty K, Aubert V, Tisseyre P, Chabert-Martinello M, Pervent M, Delaitre C, Vile D, Siol M, Duc G, Brunel B (2017) Coinoculation of a pea core-collection with diverse rhizobial strains shows competitiveness for nodulation and efficiency of nitrogen fixation are distinct traits in the interaction. Front Plant Sci 8:2249

Bravo A, Likitvivatanavong S, Gill SS, Soberón M (2011) *Bacillus thuringiensis*: a story of a successful bioinsecticide. Insect Biochem Mol Biol 41(7):423–431

Brewin NJ (1991) Development of the legume root nodule. Annu Rev Cell Biol 7:191–226

Brewin NJ, Beringer JE, Johnston AWB (1980) Plasmid mediated transfer of host range specificity between two strains of *Rhizobium leguminosarum*. J Gen Microbiol 120:413–420

Brockwell J, Bottomley PJ (1995) Recent advances in inoculant technology and prospects for the future. Soil Biol Biochem 27:683–697

Brockwell J, Bottomley PJ, Thies JE (1995) Manipulation of rhizobia microflora for improving legume productivity and soil fertility: a critical assessment. Plant Soil 174:143–180

Broughten WJ, Perret X (1999) Geneology of legume-*Rhizobium* symbioses. Curr Opinion Plant Biol 2:305–311

Broughten WJ, Jabbouri S, Perret X (2000) Keys to symbiotic harmony. J Bacteriol 182:5641–5652

Burdman S, Kigel J, Okon Y (1997) Effects of *Azospirillum brasilense* on nodulation and growth of common bean (*Phaseolus vulgaris* L.). Soil Biol Biochem 29:923–929

Burns TA, Bishop PE, Israel DW (1981) Enhanced nodulation of leguminous plant roots by mixed cultures of *Azotobacter vinelandii* and *Rhizobium*. Plant Soil 62(3):399–412

Callaham DA, Torrey JG (1981) The structural basis for infection of root hairs of *Trifolium repens* by *Rhizobium*. Can J Bot 59:1647–1664

Camacho M, Santamaria C, Temprano F, Rodriguez-Navarro DN, Daza A (2001) Coinoculation with *Bacillus* sp. CECT 450 improves nodulation in *Phaseolus vulgaris* L. Can J Microbiol 47(11):1058–1062

Cao Y, Halane MK, Gassmann W, Stacey G (2017) The role of plant innate immunity in the legume-*Rhizobium* symbiosis. Annu Rev Plant Biol 68:535–561

Carroll BJ, McNeil DL, Gresshoff PM (1985) A supernodulation and nitrate tolerant symbiotic (nts) soybean mutant. Plant Physiol 78:34–40

Cassan F, Perrig D, Sgroy V, Masciarelli O, Penna C, Luna V (2009) *Azospirillum brasilense* Az39 and *Bradyrhizobium japonicum* E109, inoculated singly or in combination, promote seed germination and early seedling growth in corn (*Zea mays* L.) and soybean (*Glycine max* L.). Eur J Soil Biol 45:28–35

Castillo M, Flores M, Mavingui P, Martinez-Romero E, Palacios R, Hernandez G (1999) Increase in alfalfa nodulation, nitrogen fixation and plant growth by specific DNA amplification in Sinorhizobium meliloti. Appl Environ Microbiol 65:2716–2722

Chaintreuil C, Giraud E, Prin Y, Lorguin J, Ba A, Gillis M, De laiudie P, Dreyfus B (2000) Photosynthetic bradyrhizobia are natural endophytes of the African wild rice *Oryza breviligulata*. Appl Environ Microbiol 66:5437–5447

Chandra S, Choure K, Dubey RC, Maheshwari DK (2007) Rhizosphere competent *Mesorhizobium loti* MP6 induces root hair curling, inhibits *Sclerotinia sclerotiorum* and enhances growth of Indian mustard (*Brassica campestris*). Braz J Microbiol 38:128–130

Chanway CP, Hynes RK, Nelson LM (1989) Plant growth promoting rhizobacteria: effect on the growth and nitrogen fixation of lentils (*Lens esculenta* Moench) and pea (*Pisum sativum* L.). Soil Biol Biochem 21:511–512

Chen C, Zhu H (2013) Are common symbiosis genes required for endophytic rice-rhizobial interactions? Plant Signal Behav 8(9):e25453

Chen YS, Shiuan D, Chen SC, Chye SM, Chen YL (2003) Recombinant truncated flagellin of *Burkholderia pseudomallei* as a molecular probe for diagnosis of melioidosis. Clin Diagn Lab Immunol 10(3):423–425

Chen WM, de Faria SM, Chou JH, James EK, Elliott GN, Sprent JI, Bontemps C, Young JP, Vandamme P (2008) *Burkholderia sabiae* sp. nov., isolated from root nodules of *Mimosa caesalpiniifolia*. Int J Syst Evol Microbiol 58(9):2174–2179

Choudhary SR, Sindhu SS (2015) Suppression of *Rhizoctonia solani* root rot disease of clusterbean (*Cyamopsis tetragonoloba*) and plant growth promotion by rhizosphere bacteria. Plant Pathol J 14:48–57

Choudhary D, Sindhu SS (2017) Amelioration of salt stress in chickpea (*Cicer arietinum* L.) by coinoculation of ACC deaminase containing rhizosphere bacteria with *Mesorhizobium* strains. Legume Res 40(1):80–86

Clawson ML, Carú M, Benson DR (1998) Diversity of *Frankia* strains in root nodules of plants from the families *Elaeagnaceae* and *Rhamnaceae*. Appl Environ Microbiol 64(9):3539–3543

Clune S, Crossin E, Verghese K (2017) Systematic review of greenhouse gas emissions for different fresh food categories. J Clean Prod 140:766–783

Cocking EC, Webster G, Batchelor CA, Davey MR (1994) Nodulation of non-legume crops: a new look. Agro-Industry Hi-Tech. 21–24

Cooper JE (2007) Early interactions between legumes and rhizobia: disclosing complexity in a molecular dialogue. J Appl Microbiol 103(5):1355–1365

Corvera A, Prome D, Prome JC, Martinez-Romero E, Romero D (1999) The nolL gene from *Rhizobium etli* determines nodulation efficiency by mediating the acetylation of the fucosyl residue in the nodulation factor. Mol Plant Microbe Interact 12:236–246

Cregan PB, Keyser HH, Sadowsky MJ (1989) Host plant effect on nodulation and competitiveness of the *Bradyrhizobium japonicum* serotype strains constituting serocluster 123. Appl Environ Microbiol 55:2532–2536

Crook MB Jr (2013) Modulators of symbiotic outcome in *Sinorhizobium meliloti*. Brigham Young University

Crutzen PJ, Mosier AR, Smith KA, Winiwarter W (2007) N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos Chem Phys Discus 7(4):11191–11205

Dadarwal KR, Sindhu SS, Batra R (1985) Ecology of Hup^+ *Rhizobium* strains of cowpea miscellany: native frequency and competence. Arch Microbiol 141:255–259

Dahale SK, Prashanthi SK, Krishnaraj PU (2016) *Rhizobium* mutant deficient in mineral phosphate solubilization activity shows reduced nodulation and plant growth in green gram. Proc Natl Acad Sci India Sect B Biol Sci 86(3):723–734

Dardanelli MS, de Cordoba FJF, Espuny MR, Carvajal MAR, Díaz MES, Serrano AMG, Okon Y, Megias M (2008) Effect of *Azospirillum brasilense* coinoculated with *Rhizobium* on *Phaseolus vulgaris* flavonoids and Nod factor production under salt stress. Soil Biol Biochem 40:2713–2721

Dashti N, Zhang F, Hynes RK, Smith DL (1998) Plant growth promoting rhizobacteria accelerate nodulation and increase nitrogen fixation activity by field grown soybean [*Glycine max* (L.) Merr.] under short season conditions. Plant Soil 200:205–213

Datta B, Chakrabartty PK (2014) Siderophore biosynthesis genes of *Rhizobium* sp. isolated from *Cicer arietinum* L. 3 Biotech 4:391–401

David H, Ian R (2000) Breeding for enhanced nitrogen fixation in crop legumes. Field Crops Res 65:229–248

Dazzo FB, Yanni YG (2006) The natural *Rhizobium*-cereal crop association as an example of plant-bacteria interaction. Biological approaches to sustainable soil systems. CRC Press, Boca Raton, pp 109–127

Debelle F, Maillet F, Vasse J, Rosenberg C, de Billy F, Truchet G, Denarie J, Ausubel FM (1988) Interference between *Rhizobium meliloti* and *Rhizobium trifolii* nodulation genes: Genetic basis of *R. meliloti* dominance. J Bacteriol 170:5718–5727

Defez R, Andreozzi A, Dickinson M, Charlton A, Tadini L, Pesaresi P, Bianco C (2017) Improved drought stress response in alfalfa plants nodulated by an IAA over-producing *Rhizobium* strain. Front Microbiol 8:2466–2473

Delamuta JR, Menna P, Ribeiro RA, Hungria M (2017) Phylogenies of symbiotic genes of *Bradyrhizobium* symbionts of legumes of economic and environmental importance in Brazil support the definition of the new symbiovars pachyrhizi and sojae. Syst Appl Microbiol 40(5):254–265

Denarie J, Debelle F, Rosenberg C (1992) Signaling and host range variation in nodulation. Annu Rev Microbiol 46(1):497–531

Denarie J, Debelle F, Prome JC (1996) *Rhizobium* lipo-chitooligosaccharide nodulation factors: Signalling molecules mediating recognition and morphogenesis. Annu Rev Biochem 65:503–535

Deshwal VK, Dubey RC, Maheshwari DK (2003) Isolation of plant growth promoting strains of *Bradyrhizobium* (Arachis) sp. with biocontrol potential against *Macrophomina phaseolina* causing charcoal rot of peanut. Curr Sci 84:443–444

Devine TE, Kuykendall LD (1996) Host genetic control of symbiosis in soybean (*Glycine max* L.). Plant Soil 186:173–187

Di Benedetto NA, Corbo MR, Campaniello D, Cataldi MP, Bevilacqua A, Sinigaglia M, Flagella Z (2017) The role of plant growth promoting bacteria in improving nitrogen use efficiency for sustainable crop production: a focus on wheat. AIMS Microbiol 3(3):413–434

Dileep Kumar BS, Berggren I, Maartensson AM (2001) Potential for improving pea production by coinoculation with fluorescent *Pseudomonas* and *Rhizobium*. Plant Soil 229:25–34

Dillewijn P, Martinez-Abarca F, Toro N (1998) Multicopy vectors carrying the *Klebsiella pneumoniae* nifA gene do not enhance the nodulation competitiveness of *Sinorhizobium meliloti* on alfalfa. Mol Plant Microbe Interact 11:839–842

Dixon R, Cheng Q, Shen GF, Day A, Day MD (1997) nif genes and expression in chloroplasts: prospects and problems. Plant Soil 194:193–203

Djordjevic MA, Zurkowski W, Shine J, Rolfe BG (1983) Sym plasmid transfer to symbiotic mutants of *Rhizobium trifolii*, *Rhizobium leguminosarum* and *Rhizobium meliloti*. J Bacteriol 156:1035–1045

Djordjevic MA, Innes RW, Wijffelman CA, Schofield PR, Rolfe BG (1986) Nodulation of specific legumes is controlled by several distinct loci in *Rhizobium trifolii*. Plant Mol Biol 6:389–401

Djordjevic MA, Mohd-Radzman NA, Imin N (2015) Small peptide signals that control nodule number, development and symbiosis. J Expt Bot 66:5171–5181. https://doi.org/10.1007/s11104-015-2445-1

Downie JA (1994) Signalling strategies for nodulation of legumes by rhizobia. Trends Microbiol 2(9):318–324

Dudley ME, Jacob TH, Long SR (1987) Microscopic studies of cell divisions induced in alfalfa roots by *Rhizobium meliloti*. Planta 171:289–301

Duhan JS, Dudeja SS, Khurana AL (1998) Siderophore production in relation to N_2 fixation and iron uptake in pigeon pea-*Rhizobium* symbiosis. Folia Microbiol 43(4):421–426

Eaglesham AR (1989) Nitrate inhibition of root-nodule symbiosis in doubly rooted soybean plants. Crop Sci 29(1):115–119

Echeverria M, Sannazzaro AI, Ruiz OA, Menéndez AB (2013) Modulatory effects of *Mesorhizobium tianshanense* and *Glomus intraradices* on plant proline and polyamine levels during early plant response of *Lotus tenuis* to salinity. Plant Soil 364:69–79

Egamberdieva D, Berg G, Lindström K, Räsänen LA (2013) Alleviation of salt stress of symbiotic *Galega officinalis* L. (goat's rue) by coinoculation of *Rhizobium* with root-colonizing *Pseudomonas*. Plant Soil 369:453–465

Elkan GH (1992) Biological nitrogen fixation systems in tropical ecosystems: an overview. In: Mulongoy K, Gueye M, Spencer DSC (eds) Biological nitrogen fixation and sustainability of tropical agriculture. Wiley, Chichester, pp 27–40

Elkoca E, Kantar F, Sahin F (2007) Influence of nitrogen fixing and phosphorus solubilizing bacteria on the nodulation, plant growth and yield of chickpea. J Plant Nutr 31:157–171

Elsheikh EA (1998) Effects of salt on rhizobia and bradyrhizobia: a review. Annal Appl Biol 132(3):507–524

Emerich DW, Ruiz-Argüeso T, Evans HJ (1979) Hydrogen-dependent nitrogenase activity and ATP formation in *Rhizobium japonicum* bacteroids. J Bacteriol 137(1):153–160

Evans HJ, Harker AR, Papen H, Russell SA, Hanus FJ, Zuber M (1987) Physiology, biochemistry and genetics of the uptake hydrogenase in rhizobia. Annu Rev Microbiol 41:355–361

Faucher C, Maillet F, Vasse J, Rosenberg C, van Brussel AN, Truchet G, Denarie J (1988) *Rhizobium meliloti* host range nodH determines production of an alfalfa-specific extracellular signal. J Bacteriol 170:5489–5499

Faucher C, Camut S, Denarie J, Truchet G (1989) The nodH and nodQ host range genes of *Rhizobium meliloti* behave as virulence genes in *R. leguminosarum* bv. *viciae* and determine changes in the production of plant-specific extracellular signals. Mol Plant Microbe Interact 2:291–300

Ferguson L, Lessenger JE (2006) Plant growth regulators. In: Lessenger JE (ed) Agricultural medicine. Springer, New York, pp 156–166

Fernández LA, Zalba P, Gómez MA, Sagardoy MA (2007) Phosphate-solubilization activity of bacterial strains in soil and their effect on soybean growth under greenhouse conditions. Biol Fertil Soils 43(6):805–809

Ferreira PAA, Lopes G, Bomfeti CA, de Oliveira Longatti SM, de Sousa Soares CRF, Guilherme LRG, de Souza Moreira FM (2013) Leguminous plants nodulated by selected strains of Cupriavidus necator grow in heavy metal contaminated soils amended with calcium silicate. World J Microbiol Biotechnol 29:2055–2066

Figueiredo MVB, Burity HA, Martínez CR, Chanway CP (2008) Alleviation of drought stress in the common bean (*Phaseolus vulgaris* L.) by coinoculation with *Paenibacillus polymyxa* and *Rhizobium tropici*. Appl Soil Ecol 40:182–188

Fischer HM (1994) Genetic regulation of nitrogen fixation in rhizobia. Microbiol Rev 58:352–386

Fleury D, Jefferies S, Kuchel H, Langridge P (2010) Genetic and genomic tools to improve drought tolerance in wheat. J Expt Bot 61:3211–3222

Fobert PR, Roy N, Nash JH, Iyer VN (1991) Procedure for obtaining efficient root nodulation of a pea cultivar by a desired *Rhizobium* strain and preempting nodulation by other strains. Appl Environ Microbiol 57:1590–1594

Fox SL, O’Hara GW, Bräu L (2011) Enhanced nodulation and symbiotic effectiveness of *Medicago truncatula* when coinoculated with *Pseudomonas fluorescens* WSM3457 and *Ensifer* (*Sinorhizobium*) *medicae* WSM419. Plant Soil 348:245

Franche C, Lindström K, Elmerich C (2009) Nitrogen-fixing bacteria associated with leguminous and non-leguminous plants. Plant Soil 321(1-2):35–59

Franzini VI, Azcon R, Mendes FL, Aroca R (2013) Different interaction among *Glomus* and *Rhizobium* species on *Phaseolus vulgaris* and *Zea mays* plant growth, physiology and symbiotic development under moderate drought stress conditions. Plant Growth Regul 70:265–273

Fravel DR (2005) Commercialization and implementation of biocontrol. Annu Rev Phytopathol 28(43):337–359

Freiberg C, Fellay R, Bairoch A, Broughton WJ, Rosenthal A, Perret X (1997) Molecular basis of symbiosis between *Rhizobium* and legumes. Nature 387:394–401

Frugier F, Kosuta S, Murray JD, Crespi M, Szczyglowski K (2008) Cytokinin: secret agent of symbiosis. Trends Plant Sci 13:115–120

Fujiata K, Ofosu-Budu KG, Ogata S (1992) Biological nitrogen fixation in mixed legume-cereal cropping systems. Plant Soil 141:155–175

Gage DJ (2004) Infection and invasion of roots by symbiotic, nitrogen-fixing rhizobia during nodulation of temperate legumes. Microbiol Mol Biol Rev 68:280–300

Gal SW, Choi YJ (2003) Isolation and characterization of salt tolerance rhizobia from *Acacia* root nodules. Agric Chem Biotechnol 46:58–62

Gamas P, Brault M, Jardinaud MF, Frugier F (2017) Cytokinins in symbiotic nodulation: when, where, what for? Trends Plant Sci 22(9):792–802

Garg FC, Garg RP, Kukreja K, Sindhu SS, Tauro P (1985) Host-dependent expression of uptake hydrogenase in cowpea rhizobia. J Gen Microbiol 131(1):93–96

Ghosh PK, Kumar De T, Maiti TK (2015) Production and metabolism of indole acetic acid in root nodules and symbiont (*Rhizobium undicola*) isolated from root nodule of aquatic medicinal legume *Neptunia oleracea* Lour. J Bot 2015:1–11

Giraud E, Moulin L, Vallenet D, Barbe V, Cytryn E, Avarre JC, Jaubert M, Simon D, Cartieaux F, Prin Y, Bena G (2007) Legumes symbioses: absence of Nod genes in photosynthetic bradyrhizobia. Science 316(5829):1307–1312

Goel AK, Sindhu SS, Dadarwal KR (1999) Bacteriocin producing native rhizobia of green gram (*Vigna radiata*) having competitive advantage in nodule occupancy. Microbiol Res 154:43–48

Goel AK, Sindhu SS, Dadarwal KR (2000) Pigment diverse mutants of *Pseudomonas* sp.: Inhibition of fungal growth and stimulation of growth of *Cicer arietinum*. Biol Plant 43:563–569

Goel AK, Sindhu SS, Dadarwal KR (2002) Stimulation of nodulation and plant growth of chickpea (*Cicer arietinum*) by *Pseudomonas* spp. antagonistic to fungal pathogens. Biol Fertil Soils 36:391–396

Gopalakrishnan S, Sathya A, Vijayabharathi R, Varshney RK, Gowda CL, Krishnamurthy L (2015) Plant growth promoting rhizobia: challenges and opportunities. 3 Biotech 5:355–377

Gough C, Vasse J, Galera C, Webster G, Cocking E, Denarie J (1997) Interactions between bacterial diazotrophs and non-legume dicots: *Arabdiopsis thaliana* as a model plant. Plant Soil 194:123–130

Graham PH (1992) Stress tolerance in *Rhizobium* and *Bradyrhizobium* and nodulation under adverse soil conditions. Can J Microbiol 38(6):475–484

Gresshoff PM (2003) Post-genomic insights into plant nodulation symbioses. Genome Biol 4:201. https://doi.org/10.1186/gb-2003-4-1-201

Grimes HD, Mount MS (1984) Influence of *Pseudomonas putida* on nodulation of *Phaseolus vulgaris*. Soil Biol Biochem 16:27–30

Grover M, Ali SZ, Sandhya V, Rasul A, Venkateswarlu B (2011) Role of microorganisms in adaptation of agriculture crops to abiotic stresses. World J Microbiol Biotechnol 27(5):1231–1240

Guefrachi I, Rejili M, Mahdhi M, Mars M (2013) Assessing genotypic diversity and symbiotic efficiency of five rhizobial legume interactions under cadmium stress for soil phytoremediation. Int J Phytorem 15:938–951

Gully D, Teulet A, Busset N, Nouwen N, Fardoux J, Rouy Z, Vallenet D, Cruveiller S, Giraud E (2017) Complete genome sequence of *Bradyrhizobium* sp. ORS285, a photosynthetic strain able to establish Nod factor-dependent or Nod factor-independent symbiosis with *Aeschynomene* legumes. Genome Announc 5(30):e00421–e00417

Gusain YS, Singh US, Sharma AK (2015) Bacterial mediated amelioration of drought stress in drought tolerant and susceptible cultivars of rice (*Oryza sativa* L.). Afr J Biotechnol 14:764–773

Haggag WM, Abouziena HF, Abd-El-Kreem F, Habbasha S (2015) Agriculture biotechnology for management of multiple biotic and abiotic environmental stress in crops. J Chem Pharm 7(10):882–889

Halverson LJ, Handelsman J (1991) Enhancement of soybean nodulation by *Bacillus cereus* UW85 in the field and in a growth chamber. Appl Environ Microbiol 57:2767–2770

Hanin M, Jabbouri S, Quesada-Vincens D, Freiberg C, Perret X, Prome JC, Broughten WJ, Fallay R (1997) Sulphation of *Rhizobium* sp. NGR234 Nod factors is dependent on noeE, a new host specificity gene. Mol Biol 24:1119–1129

Hanin M, Jabbouri S, Broughten WJ, Fallay R, Quesada-Vincens D (1999) Molecular aspects of host specific nodulation. In: Stacey G, Keen NT (eds) Plant microbe interactions, vol 4. APS Press, St. Paul, pp 1–37

Hansen AP, Peoples MB, Gresshoff PM, Atkins CA, Pate JS, Carroll BJ (1989) Symbiotic performance of supernodulating soybean [*Glycine max* (L.) Merr.] mutants during development on different nitrogen regimes. J Expt Bot 40:715–724

Hansena JC, Schillingerb WF, Sullivanb TS, Paulitzc TC (2018) Rhizosphere microbial communities of canola and wheat at six paired field sites. Appl Soil Ecol. https://doi.org/10.1016/j.apsoil.2018.06.012

Hanus FJ, Albrecht SL, Zablotowicz RM, Emerich DW, Russell SA, Evans HJ (1981) Yield and N content of soybean seed as influenced by *Rhizobium japonicum* inoculants possessing the uptake hydrogenase characteristics. Agron J 73:368–372

Hara-Nishimura I, Hatsugai N, Nakaune S, Kuroyanagi M, Nishimura M (2005) Vacuolar processing enzyme: an executor of plant cell death. Curr Opin Plant Biol 8:404–408. https://doi.org/10.1016/j.pbi.2005.05.016

Hardarson G (1993) Methods for enhancing symbiotic nitrogen fixation. Plant Soil 152(1):1–7

Hardarson G, Heichel GH, Barnes DK, Vance CP (1982) Rhizobial strain preference of alfalfa populations selected for characteristics associated with N_2 fixation. Crop Sci 22:55–58

Hardy RWF, Havelka UD (1975) Nitrogen fixation research: a key to world food? Science 188:633–643

Hegazi NA, Vlassak K, Monib M (1979) Effect of amendments, moisture and temperature on acetylene reduction in Nile Delta soil. Plant Soil 51:27–37

Hemissi I, Mabrouk Y, Mejri S, Saidi M, Sifi B (2013) Enhanced defence responses of chickpea plants against *Rhizoctonia solani* by pre-inoculation with rhizobia. J Phytopathol 161:412–418

Herridge DF, Peoples MB, Boddey RM (2008) Global inputs of biological nitrogen fixation in agricultural systems. Plant Soil 311(1–2):1–8

Holl FB, Chanway CP, Turkington R, Radley RA (1988) Response of crested wheatgrass (*Agrepyron cristatum* L.), perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) to inoculation with *Bacillus polymyxa*. Soil Biol Biochem 20:19–24

Hooykaas PJJ, van Brussel AAN, Den Dulk Ras H, van Slogteren GMS, Schilperoort RA (1981) Sym-plasmid of *Rhizobium trifolii* expressed in different rhizobial species and *Agrobacterium tumefaciens*. Nature 291:351–353

Hooykaas PJJ, Snijdewint FGM, Schilperoort RA (1982) Identification of the sym plasmid of *Rhizobium leguminosarum* strain 1001 and its transfer to and expression in other rhizobia and *Agrobacterium tumefaciens*. Plasmid 8:73–82

Hungaria M, Neves MCP, Dobreiner J (1989) Relative efficiency, ureide transport and harvest index in soybeans inoculated with isogenic Hup$^-$ mutants of *Bradyrhizobium japonicum*. Biol Fertil Soils 7:325–329

Hussain MB, Zahir ZA, Asghar HN (2014a) Can catalase and EPS producing rhizobia ameliorate drought in wheat? Int J Agric Biol 16:3–13

Hussain MB, Zahir ZA, Asghar HN, Mahmood S (2014b) Scrutinizing rhizobia to rescue maize growth under reduced water conditions. Soil Sci Soc Am J. https://doi.org/10.2136/sssaj2013.07.0315

Iqbal MA, Khalid M, Shahzad SM, Ahmad M, Soleman N, Akhtar N (2012) Integrated use of *Rhizobium leguminosarum*, plant growth promoting rhizobacteria and enriched compost for improving growth, nodulation and yield of lentil (*Lens culinaris* Medik.). Chil J Agric Res 72:104–110

Iruthayathas EE, Gunasekaran S, Vlassak K (1983) Effect of combined inoculation of *Azospirillum* and *Rhizobium* on nodulation and N_2-fixation of winged bean and soybean. Scientia Horti 20(3):231–240

Ishizuka J (1992) Trends in biological nitrogen fixation research and application. Plant Soil 141:197–209

Islam MZ, Sattar MA, Ashrafuzzaman M, Berahim Z, Shamsuddoha ATM (2013) Evaluating some salinity tolerant rhizobacterial strains to lentil production under salinity stress. Int J Agric Biol 15:499–504

Itzigsohn R, Kapulnik Y, Okon Y, Dovrat A (1993) Physiological and morphological aspects of interaction between *Rhizobium meliloti* and alfalfa (*Medicago sativa*) in association with *Azospirillum brasilense*. Can J Microbiol 39:610–615

Jabbouri S, Fallay R, Telmont F, Kamalapriya P, Burger U, Relic B, Prome JC, Broughten WJ (1995) Involvement of *nod*S in N-methylation and *nod*U in 6-O-carbomylation of *Rhizobium* sp. NGR234 Nod factors. J Biol Chem 270:22968–22973

Jacobson MR, Premakumar R, Bishop PE (1986) Transcriptional regulation of nitrogen fixation by molybdenum in *Azotobacter vinelandii*. J Bacteriol 167:480–486

Jensen ES, Hauggaard-Nielsen H (2003) How can increased use of biological N_2 fixation in agriculture benefit the environment? Plant Soil 252(1):177–186

Jensen ES, Peoples MB, Boddey RM, Gresshoff PM, Hauggaard-Nielsen H, Alves BJ, Morrison MJ (2012) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries: a review. Agron Sustain Dev 32:329–364

Jeuffroy MH, Baranger E, Carrouée B, Chezelles ED, Gosme M, Hénault C (2013) Nitrous oxide emissions from crop rotations including wheat, oilseed rape and dry peas. Biogeosciences 10:1787–1797

Joseph B, Patra RR, Lawrence R (2007) Characterization of plant growth promoting rhizobacteria associated with chickpea (*Cicer arietinum* L.). Int J Plant Prod 2:141–152

Jangu OP, Sindhu SS (2011) Differential response of inoculation with acetic acid producing *Pseudomonas* sp. in green gram (*Vigna radiata* L.) and blck gram (*Vigna mungo* L.). Microbiol J 1:159–173

Kaló P, Gleason C, Edwards A, Marsh J, Mitra RM, Hirsch S, Jakab J, Sims S, Long SR, Rogers J, Kiss GB, Downie JA, Oldroyd GED (2005) Nodulation signaling in legumes requires NSP2, a member of the GRAS family of transcriptional regulators. Science 308:1786–1789

Kalra N, Suneja P, Mendiratta N, Gupta N (2013) Simulating the impact of climate change and its variability on growth and yield of crops. Clim Chang Environ Sustain 1(1):11–19

Karaman MR, Sahin S, Düzdemir O, Kandemir N (2013) Selection of chickpea cultivars with agronomic phosphorus (P) utilization characters as influenced by *Rhizobium* inoculation. Sci Res Essays 8:676–681

Karasu A, Dogan R (2009) The effect of bacterial inoculation and different nitrogen doses on yield and yield components of some chickpea genotypes (*Cicer arietinum* L.). Afr J Biotechnol 8(1):59–64

Karunakaran R, Ramachandran VK, Seaman JC, East AK, Mouhsine B, Prell J, Skeffington A, Poole PS (2009) Transcriptomic analysis of *Rhizobium leguminosarum* biovar *viciae* in symbiosis with host plants *Pisum sativum* and *Vicia cracca*. J Bacteriol 191:4002–4014. https://doi.org/10.1128/jb.00165-09

Kassaw T, Jr W, Frugoli J (2015) Multiple autoregulation of nodulation (AON) signals identified through split root analysis of *Medicago truncatula* sunn and rdn1 mutants. Plants 4(2):209–224

Kennedy IR, Tchan YT (1992) Biological nitrogen fixation in non-leguminous field crops: recent advances. Plant Soil 141:93–118

Kennedy IR, Pereg-Gerk LL, Wood C, Deaker R, Gilcrest K, Katupitia S (1997) Biological nitrogen fixation in non-leguminous field crops: facilitating the evolution of an effective association between *Azospirillum* and wheat. Plant Soil 194:65–79

Keum YS, Seo JS, Hu YT, Li QX (2006) Degradation pathways of phenanthrene by *Sinorhizobium* sp. C4. Appl Microbiol Biotechnol 71:935–941. https://doi.org/10.1007/s00253-005-0219-z

Khan MS, Zaidi A, Aamil M (2002) Biocontrol of fungal pathogens by the use of plant growth promoting rhizobacteria and nitrogen fixing microorganisms. Ind J Bot Soc 81:255–263

Khanna V, Sharma P (2011) Potential for enhancing lentil (*Lens culinaris*) productivity by co-inoculation with PSB, plant growth-promoting rhizobacteria and *Rhizobium*. Indian J Agric Sci 81(10):932–937

Khot GG, Tauro P, Dadarwal KR (1996) Rhizobacteria from chickpea (*Cicer arietinum* L.) rhizosphere effective in wilt control and promote nodulation. Ind J Microbiol 36:217–222

Kijne JW, Smith G, Diaz CL, Lugtenberg BJJ (1988) Lectin-enhanced accumulation of manganese-limited *Rhizobium leguminosarum* cells on pea root hair tips. J Bacteriol 170:2994–3000

Kim YC, Glick BR, Bashan Y, Ryu CM (2012) Enhancement of plant drought tolerance by microbes. In: Aroca R (ed) Springer, pp 383–413

Kinkle BK, Sadowsky MJ, Schmidt EL, Koskinen WC (1993) Plasmids pJP4 and R68.45 can be transferred between populations of bradyrhizobia in nonsterile soil. Appl Environ Microbiol 59:1762–1766

Knight TJ, Langston-Unkefer PJ (1988) Enhancement of symbiotic dinitrogen fixation by a toxin-releasing plant pathogen. Science 241:951–954

Kondorosi A, Vincze E, Johnston AWB, Beringer JE (1980) A comparison of three *Rhizobium* linkage maps. Mol Gen Genet 178:403–408

Kondorosi A, Kondorosi E, Pankhurst CE, Broughton WJ, Banfalvi Z (1982) Mobilization of *Rhizobium meliloti* megaplasmid carrying nodulation and nitrogen fixation genes in other rhizobia and *Agrobacterium*. Mol Gen Genet 188:433–439

Krishnan HB, Lewin A, Fallay R, Broughten WJ, Pueppke SG (1992) Differential expression of nodS accounts for the varied abilities of *Rhizobium fredii* USDA257 and *Rhizobium* sp. NGR234 to nodulate *Leucaena* spp. Mol Biol 6:3321–3330

Krishnan HB, Kim KY, Krishnan AH (1999) Expression of a *Serratia marcescens* chitinase gene in *Sinorhizobium fredii* USDA191 and *Sinorhizobium meliloti* RCR2011 impedes soybean and alfalfa nodulation. Mol Plant Microbe Interact 12:748–751

Kucey RM, Hynes MF (1989) Populations of *Rhizobium leguminosarum* biovars *phaseoli* and *viceae* in fields after bean or pea in rotation with nonlegumes. Can J Microbiol 35(6):661–667

Kulkarni S, Nautiyal CS (2000) Effects of salt and pH stress on temperature-tolerant *Rhizobium* sp. NBRI330 nodulating *Prosopis juliflora*. Curr Microbiol 40:221–226

Kumar G, Ram MR (2014) Phosphate solubilizing rhizobia isolated from *Vigna trilobata*. Am J Microbiol Res 2:105–109

Lahrouni M, Oufdou K, El Khalloufi F, Baz M, Lafuente A, Dary M, Pajuelo E, Oudra B (2013) Physiological and biochemical defense reactions of *Vicia faba* L.–*Rhizobium* symbiosis face to chronic exposure to cyanobacterial bloom extract containing microcystins. Environ Sci Pollut Res 20:5405–5415

Larrainzar E, Riely B, Kim SC, Carrasquilla-Garcia N, Yu HJ, Hwang HJ, Oh M, Kim GB, Surendrarao A, Chasman D, Siahpirani AF, Penmetsa RV, Lee GS, Kim N, Roy S, Mun JH, Cook DR (2015) Deep sequencing of the *Medicago truncatula* root transcriptome reveals a massive and early interaction between Nod factor and ethylene signals. Plant Physiol 169(1):233–265. https://doi.org/10.1104/pp.15.00350

Lerouge P, Roche P, Faucher C, Maillet F, Truchet G, Prome JC, Denarie J (1990) Symbiotic host-specificity of *Rhizobium meliloti* is determined by a sulphated and acylated glucosamine oligosaccharide signal. Nature 344:781–784

Levy J, Bres C, Geurts R, Chalhoub B, Kulikova O, Duc G, Journet EP, Ane JM, Lauber E, Bisseling T, Denarie J, Rosenberg C, Debelle F (2004) A putative Ca^{2+} and calmodulin-dependent protein kinase required for bacterial and fungal symbioses. Science 303:1361–1364

Lewin A, Cervantes E, Wong CH, Broughton WJ (1990) nodSU, two new nod genes of the broad host-range *Rhizobium* strain NGR234 encode host specific nodulation of the tropical tree *Leucaena leucocephala*. Mol Plant Microbe Interact 3:317–326

Li DM, Alexander M (1988) Coinoculation with antibiotic-producing bacteria to increase colonization and nodulation by rhizobia. Plant Soil 108:211–219

Li Y, Zhou L, Chen D, Tan X, Lei L, Zhou J (2008) A nodule-specific plant cysteine proteinase, AsNODF32, is involved in nodule senescence and nitrogen fixation activity of the green manure legume *Astragalus sinicus*. New Phytol 180:185–192. https://doi.org/10.1111/j.1469-8137.2008.02562.x

Lievens S, Goormachtig S, Den Herder J, Capoen W, Mathis R, Hedden P, Holsters M (2005) Gibberellins are involved in nodulation of *Sesbania rostrata*. Plant Physiol 139:1366–1379

Lim JH, Kim SD (2013) Induction of drought stress resistance by multi-functional PGPR *Bacillus licheniformis* K11 in pepper. Plant Pathol J 29:201–208

Lindström K, Kokko-Gonzales P, Terefework Z, Räsänen LA (2006) Differentiation of nitrogen-fixing legume root nodule bacteria (rhizobia). Molecular approaches soil, rhizosphere and plant microorganism analysis, p 236

Liu L, Kloepper JW, Tuzun S (1995a) Induction of systemic resistance in cucumber against bacterial angular leaf spot by plant growth-promoting rhizobacteria. Phytopathology 85(8):843–847

Liu L, Kloepper JW, Tuzun S (1995b) Induction of systemic resistance in cucumber against Fusarium wilt by plant growth-promoting rhizobacteria. Phytopathology 85(6):695–698

Loh J, Stacey G (2003) Nodulation gene regulation in *Bradyrhizobium japonicum*: a unique integration of global regulatory circuits. Appl Environ Microbiol 69:10–17

Long SR (1989) *Rhizobium* genetics. Annu Rev Genet 23:483–506

Long SR (1996) *Rhizobium* symbiosis: nod factors in perspective. Plant Cell 8:1885–1898

Loper J, Schroth M (1986) Influence of bacteria sources of indol-3-acetic acid on root elongation of sugar beet. Phytopathol 76:386–389

Lopez-Lara IM, Blok-Tip L, Quinto C, Garcia ML, Bloemberg GV, Lamers GEM, Kafetzopoulos D, Stacey G, Lugtenberg BJJ, Thomas-Oates JE, Spaink HP (1996) *nod*Z of *Bradyrhizobium* extends the nodulation host range of *Rhizobium* by adding a fucosyl residue to nodulation factors. Mol Microbiol 21:397–408

Lu YL, Chen WF, Wang ET, Guan SH, Yan XR, Chen WX (2009) Genetic diversity and biogeography of rhizobia associated with *Caragana* species in three ecological regions of China. Syst Appl Microbiol 32(5):351–361

Lynch JM (1983) Microorganisms and enzymes in the soil. In: Marumoto T, Watanabe I, Satoh K, Kanazawa S (eds) Soil biotechnology, microbiological factors in crop productivity. Blackwell Science Publications, London, p 185

Machado RG, de Sá EL, Bruxel M, Giongo A, da Silva Santos N, Nunes AS (2013) Indole acetic acid producing rhizobia promote growth of Tanzania grass (*Panicum maximum*) and Pensacola grass (*Paspalum saurae*). Int J Agric Biol 15:827–834

Martinez E, Palacios R, Sanchez F (1987) Nitrogen-fixing nodules induced by *Agrobacterium tumefaciens* harboring *Rhizobium phaseoli* plasmids. J Bacteriol 169:2828–2834

Mateos PF, Baker DL, Philip-Hollingsworth S, Sqartini A, Peruffo ADB, Nuti MP, Dazzo F (1995) Direct in situ identification of cellulose microfibrils associated with *Rhizobium leguminosarum* biovar *trifolii* attached to the root epidermis of white clover. Can J Microbiol 41:202–207

Mathews A, Carroll BJ (2018) Nitrate inhibition of nodulation in legumes. In: Molecular biology of symbiotic nitrogen fixation. CRC Press, Boca Raton, pp 159–180

Mavingui P, Flores M, Romero D, Martinez-Romero E, Palacios R (1997) Generation of *Rhizobium* strains with improved symbiotic properties by random DNA amplification (RDA). Nat Biotechnol 15:564–569

Mayak S, Tirosh T, Glick BR (2004a) Plant growth-promoting bacteria confer resistance in tomato plants to salt stress. Plant Physiol Biochem 42:565–572

Mayak S, Tirosh T, Glick BR (2004b) Plant growth-promoting bacteria that confer resistance to water stress in tomatoes and peppers. Plant Sci 166:525–530

McIver J, Djordjevic MA, Weinman JJ, Bender GL, Rolfe BG (1989) Extension of host range of *Rhizobium leguminosarum* bv. *trifolii* caused by point mutations in nodD that result in alterations in regulatory function and recognition of inducer molecules. Mol Plant Microbe Interact 2:97–106

Mendoza A, Leija A, Martinez-Romero E, Hernandez G, Mora J (1995) The enhancement of ammonium assimilation in *Rhizobium elti* prevents nodulation of *Phaseolus vulgaris*. Mol Plant Microbe Interact 8:584–592

Mendoza A, Valderrama B, Leija A, Mora J (1998) NifA-dependent expression of glutamate dehydrogenase in *Rhizobium etli* modifies nitrogen partitioning during symbiosis. Mol Plant Microbe Interact 11:83–90

Menna P, Hungria M, Barcellos FG, Bangel EV, Hess PN, Martínez-Romero E (2006) Molecular phylogeny based on the 16S rRNA gene of elite rhizobial strains used in Brazilian commercial inoculants. Syst Appl Microbiol 29(4):315–332

Merberg D, Maier RJ (1983) Mutants of *Rhizobium japonicum* with increased hydrogenase activity. Science 220:1064–1065

Mfilinge A, Mtei K, Ndakidemi P (2014) Effect of *Rhizobium* inoculation and supplementation with phosphorus and potassium on growth and total leaf chlorophyll (Chl) content of bush bean *Phaseolus vulgaris*, L. Agri Sci 5:1413–1419

Mhadhbi H, Jebara M, Limam F, Aouani ME (2004) Rhizobial strain involvement in plant growth, nodule protein composition and antioxidant enzyme activities of chickpea–rhizobia symbioses: modulation by salt stress. Plant Physiol Biochem 42:717–722

Miller RH, May S (1991) Legume inoculation: successes and failures. In: Keister DL, Cregan PB (eds) The rhizosphere and plant growth. Kluwer, Dordrecht, pp 123–134

Miller-Williams M, Loewen PC, Oresnik IJ (2006) Isolation of salt-sensitive mutants of *Sinorhizobium meliloti* strain Rm1021. Microbiology 152(7):2049–2059

Miransari M, Smith D (2009) Rhizobial lipo-chitooligosaccharides and gibberellins enhance barley (*Hordeum vulgare* L.) seed germination. Biotechnology 8:270–275

Mishra NS, Tuteja R, Tuteja N (2006) Signaling through MAP kinase networks in plants. Arch Biochem Biophys 452(1):55–68
Mishra PK, Mishra S, Selvakumar G, Bisht JK, Kundu S, Gupta HS (2009) Coinoculation of *Bacillus thuringiensis*-KR1 with *Rhizobium leguminosarum* enhances plant growth and nodulation of pea (*Pisum sativum* L.) and lentil (*Lens culinaris* L.). World J Microbiol Biotechnol 25:753–761
Mishra PK, Bisht SC, Ruwari P, Joshi GK, Singh G, Bisht JK, Bhatt JC (2011) Bioassociative effect of cold tolerant *Pseudomonas* spp. and *Rhizobium leguminosarum* PR1 on iron acquisition, nutrient uptake and growth of lentil (*Lens culinaris* L.). Eur J Soil Biol 47:35–43
Miwa H, Sun J, Oldroyd GED, Allan Downie J (2006) Analysis of calcium spiking using a cameleon calcium sensor reveals that nodulation gene expression is regulated by calcium spike number and the developmental status of the cell. Plant J 48:883–894
Mondal HK, Mehta S, Kaur H, Gera R (2017) Characterization of stress tolerant mungbean rhizobia as PGPR and plant growth promotion under abiotic stress. Indian J Microbiol 44(4):38–42
Morel MA, Braña V, Castro-Sowinski S (2012) Legume crops, importance and use of bacterial inoculation to increase production. InCrop Plant 2012. InTech
Mortier V, Den Herder G, Whitford R, Van de Velde W, Rombauts S, D'Haeseleer K, Holsters M, Goormachtig S (2010) CLE peptides control *Medicago truncatula* nodulation locally and systemically. Plant Physiol 153:222–237
Mortier V, De Wever E, Vuylsteke M, Holsters M, Goormachtig S (2012) Nodule numbers are governed by interaction between CLE peptides and cytokinin signaling. Plant J 70:367–376
Mytton LR, Brockwell J, Gibson AH (1984) The potential for breeding an improved legume-*Rhizobium* symbiosis: assessment of genetic variation. Euphytica 33:401–410
Malik DK, Sindhu SS (2008) Transposon derived mutants of *Pseudomonas* strains altered in indole acetic acid production: effect on nodulation and plant growth in green gram (*Vigna radiata*). Physiol Mol Biol Plants 14:315–320
Nambiar PT, Ma SW, Iyer VN (1990) Limiting an insect infestation of nitrogen-fixing root nodules of the pigeon pea (*Cajanus cajan*) by engineering the expression of an entomocidal gene in its root nodules. Appl Environ Microbiol 56(9):2866–2869
Nedumaran S, Abinaya P, Jyosthnaa P, Shraavya B, Rao P, Bantilan C (2015) Grain legumes production, consumption and trade trends in developing countries. ICRISAT Res Progr Mark Inst Polic Work Pap Ser 60:4–7
Newbould P (1989) The use of nitrogen fertilizer in agriculture: where do we go practically and ecologically? Plant Soil 115:297–311
Nieuwkoop AJ, Banfalvi Z, Deshmane N, Gerhold D, Schell MG, Sirotkin KM, Stacey G (1987) A locus encoding host range is linked to the common nodulation genes of *Bradyrhizobium japonicum*. J Bacteriol 169:2631–2638
Nishijima F, Evans WR, Vesper SJ (1988) Enhanced nodulation of soybean by *Bradyrhizobium* in the presence of *Pseudomonas fluorescens*. Plant Soil 111:149–150
Norel F, Elmerich C (1987) Nucleotide sequence and functional analysis of the two nifH copies of *Rhizobium* ORS571. J Gen Microbiol 133:1563–1576
Nutman PS (1984) Improving nitrogen fixation in legumes by plant breeding: The relevance of host selection experiments in red clover (*Trifolium pretense* L.) and subterraneum clover (*T. subterraneum* L.). Plant Soil 82:285–301
Nyoki D, Ndakidemi PA (2014) Effects of phosphorus and *Bradyrhizobium japonicum* on growth and chlorophyll content of cowpea (*Vigna unguiculata* (L) Walp). Am J Exp Agric 4:1120–1136
O'Connell KP, Goodman RM, Handelsman J (1996) Engineering the rhizosphere: a expressing a bias. Trends Biotechnol 14:83–86
Oldroyd GE, Downie JA (2008) Coordinating nodule morphogenesis with rhizobial infection in legumes. Annu Rev Plant Biol 59:519–546
Oldroyd GE (2013) Speak, friend, and enter: signalling systems that promote beneficial symbiotic associations in plants. Nature Rev Microbiol 11(4):252

Osborn AM (2006) Horizontal gene transfer and its role in the emergence of new phenotypes. In: Logan NA, Lappin-Scott HM, Oyston PCF (eds) SGM sumposium 66: procaryotic diversity, mechanisms and significance. Cambridge University Press, Cambridge, pp 275–292

Oufdou K, Benidire L, Lyubenova L, Daoui K, Fatemi ZEA, Schröder P (2014) Enzymes of the glutathioneascorbate cycle in leaves and roots of rhizobia inoculated faba bean plants (*Vicia faba* L.) under salinity stress. Eur J Soil Biol 60:98–103

Papworth A, Maslin M, Randalls S (2015) Is climate change the greatest threat to global health? Geogr J 181:413–422

Parke D, Rivelli M, Ornston LN (1985) Chemotaxis to aromatic and hydroaromatic acids: comparison of *Bradyrhizobium japonicum* and *Rhizobium trifolii*. J Bacteriol 163:417–422

Passatore L, Rossetti S, Juwarkar AA, Massacci A (2014) Phytoremediation and bioremediation of polychlorinated biphenyls (PCBs): state of knowledge and research perspectives. J Hazard Mater 278:189–202. https://doi.org/10.1016/j.jhazmat.2014.05.051

Patriarca EJ, Tate R, Ioccarino M (2002) Key role of NH_4^+ metabolism in *Rhizobium*-plant symbiosis. Microbiol Mol Biol Rev 66:203–222. https://doi.org/10.1128/mmbr.66.2.203-222.2002

Pau AS (1991) Improvement of *Rhizobium* inoculants by mutation, genetic engineering and formulation. Biotechnol Adv 9:173–184

Peoples MB, Herridge DF (1990) Nitrogen fixation by legumes in tropical and subtropical agriculture. In: Advances in agronomy, vol 44. Academic, San Diego, pp 155–223

Peoples MB, Boyer EW, Goulding KW, Heffer P, Ochwoh VA, van Lauwe B, Wood S, Yagi K, van Cleemput O (2004) Pathways of nitrogen loss and their impacts on human health and the environment. Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment. Mosier AR, Sayers JR, Freney JR. SCOPE 65. Island Press, Washington, DC, 53–69

Peoples MB, Brockwell J, Herridge DF, Rochester IJ, Alves BJ, Urquiaga S, Boddey RM, Dakora FD, Bhattarai S, Maskey SL, Sampet C (2009) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48(1-3):1–7

Perret X, Staehelin C, Broughton WJ (2000) Molecular basis of symbiotic promiscuity. Microbiol Mol Biol Rev 64(1):180–201

Pinto FGS, Hungaria M, Mercante FM (2007) Polyphasic characterization of Brazilian *Rhizobium tropici* strains effective in fixing N_2 with common bean (*Phaseolus vulgaris* L.). Soil Biol Biochem 39:1851–1864

Pladys D, Dmitrijevic L, Rigaud J (1991) Localization of a protease in protoplast preparations in infected cells of French bean nodules. Plant Physiol 97:1174–1180

Plazinski J, Ridge RW, McKay IA, Djordjevic MA (1994) The nod ABC genes of *Rhizobium leguminosarum* biovar trifolii confer root-hair curling ability to a diverse range of soil bacteria and the ability to induce novel root swellings on beans. Aus J Plant Physiol 21:311–325

Podile AR (1995) Seed bacterization with *Bacillus subtilis* AF1 enhances seedling emergence, growth and nodulation of pigeonpea. Indian J Microbiol 35:199–204

Polcyn W, Luciński R (2003) Aerobic and anaerobic nitrate and nitrite reduction in free-living cells of *Bradyrhizobium* sp. (Lupinus). FEMS Microbiol Lett 226(2):331–337

Poonthrigpun S, Pattaragulwanit K, Paengthai S, Kriangkripipat T, Juntongjin K, Thaniyavarn S, Petsom A, Pinphanichakarn P (2006) Novel intermediates of acenaphthylene degradation by *Rhizobium* sp. strain CU-A1: evidence for naphthalene-1,8- dicarboxylic acid metabolism. Appl Environ Microbiol 72:6034–6039. https://doi.org/10.1128/AEM.00897-06

Prabha C, Maheshwari DK, Bajpai VK (2013) Diverse role of fast growing rhizobia in growth promotion and enhancement of psoralen content in *Psoralea corylifolia* L. Pharmacogn Mag 9:S57–S65

Pracht JE, Nickell CD, Harper JE, Bullock DG (1994) Agronomic evaluation of non-nodulating and hypernodulating mutants of soybean. Crop Sci 34:738–740

Prasad R, Kumar M, Varma A (2015) Role of PGPR in soil fertility and plant health. In: Plant-growth-promoting rhizobacteria (PGPR) and medicinal plants. Springer, Cham, pp 247–260

Probanza A, Lucas J, Acero N, Mañero FG (1996) The influence of native rhizobacteria on European alder (*Alnus glutinosa* (L.) Gaertn.) growth. Plant Soil 182:59–66

Putnoky P, Kondorosi A (1986) Two gene clusters of *Rhizobium meliloti* code for early essential nodulation functions and a third influences nodulation efficiency. J Bacteriol 167:881–887

Quain MD, Makgopa ME, Márquez-García B, Comadira G, Fernandez-Garcia N, Olmos E, Schnaubelt D, Kunert KJ, Foyer CH (2014) Ectopic phytocystatin expression leads to enhanced drought stress tolerance in soybean (*Glycine max*) and *Arabidopsis thaliana* through effects on strigolactone pathways and can also result in improved seed traits. Plant Biotechnol J 12:903–913. https://doi.org/10.1111/pbi.12193

Quain MD, Makgopa ME, Cooper JW, Kunert KJ, Foyer CH (2015) Ectopic phytocystatin expression increases nodule numbers and influences the responses of soybean (*Glycine max*) to nitrogen deficiency. Phytochemistry 112:179–187. https://doi.org/10.1016/j.phytochem.2014.12.027

Quesada-Vincens D, Fallay R, Nassim T, Viprey V, Burger U, Prome JC, Broughten WJ, Jabbouri S (1997) *Rhizobium* sp. NGR234 NodZ protein is a fucosyltransferase. J Bacteriol 179:5087–5093

Quinto C, de la Vega H, Flores M, Leemans J, Cevallos MA, Pardo MA, Azpiroz R, de Lourdes GM, Calva E, Palacois R (1985) Nitrogenase reductase: a functional multigene family in *Rhizobium phaseoli*. Proc Natl Acad Sci U S A 82:1170–1174

Quispel A (1988) Bacteria-plant interactions in symbiotic nitrogen fixation. Physiol Plant 74:783–790. https://doi.org/10.1111/j.1399-3054.1988.tb02052.x

Rahmani H, Saleh-Rastin N, Khavazi K, Asgharzadeh A, Fewer D, Kiani S, Lindstrom K (2009) Selection of thermotolerant bradyrhizobial strains for nodulation of soybean (*Glycine max* L.) in semi-arid regions of Iran. World J Microbiol Biotechnol 25:591–600

Rajendran G, Sing F, Desai AJ, Archana G (2008) Enhanced growth and nodulation of pigeon pea by coinoculation of *Bacillus* strains with *Rhizobium* spp. Bioresour Technol 99:4544–4550

Rajwar A, Sahgal M, Johri BN (2013) Legume-rhizobia symbiosis and interactions in agroecosystems. In: Arora NK (ed) Plant microbe symbiosis-fundamentals and advances. Springer, New Delhi, pp 233–265

Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M, Rieseberg LH (2018) Trends in global agricultural land use: implications for environmental health and food security. Annu Rev Plant Biol 69:789–815

Rao SSR, Vardhini BV, Sujatha E, Anuradha S (2002) Brassinosteroids–a new class of phytohormones. Curr Sci 82:1239–1245

Raverkar KP, Konde BK (1988) Effect of *Rhizobium* and *Azospirillum lipoferum* inoculation on the nodulation, yield and nitrogen uptake of peanut cultivars. Plant Soil 106(2):249–252

Ravikumar R (2012) Growth effects of *Rhizobium* inoculation in some legume plants. Intern J Curr Sci 1:1–6

Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, Crutzen PJ (2012) Global agriculture and nitrous oxide emissions. Nat Clim Change 2:410–416

Reckling M, Hecker JM, Bergkvist G, Watson CA, Zander P, Schläfke N, Stoddard FL, Eory V, Topp CF, Maire J, Bachinger J (2016) A cropping system assessment framework–evaluating effects of introducing legumes into crop rotations. Eur J Agron 76:186–197

Rehman N, Ali M, Ahmad MZ, Liang G, Zhao J (2018) Strigolactones promote rhizobia interaction and increase nodulation in soybean (*Glycine max*). Microbiol Pathol 114:420–430

Reimann S, Hauschild R, Hildebrandt U, Sikora RA (2008) Interrelationships between *Rhizobium etli* G12 and *Glomus intraradices* and multitrophic effects in the biological control of the root-knot nematode *Meloidogyne incognita* on tomato. J Plant Dis Protect 115:108–113

Relic B, Talmont F, Kopcinska J, Golinowsky W, Prome JC, Broughten WJ (1993) Biological activity of *Rhizobium* sp. NGR234 Nod-factors on *Macroptillium atropurpureum*. Mol Plant Microbe Interact 6:764–774

Relic B, Perret X, Estrada-Garcia J, Kopcinska J, Golinowsky W, Krishnan HB, Pueppke SG, Broughten WJ (1994) Nod-factors of *Rhizobium* are a key to legume door. Mol Microbiol 13:171–178

Remans R, Croonenborghs A, Torres-Gutierrez R, Michiels J, Vanderleyden J (2007) Effects of plant growth promoting rhizobacteria on nodulation of *Phaseolus vulgaris* L. are dependent on plant nutrition. Eur J Plant Pathol 119:341–351

Remans R, Ramaekers L, Schalkens S, Hernandez G, Garcia A, Reyes JL, Mendez N, Toskano V, Mulling M, Galvez L, Vanderleyden J (2008) Effect of *Rhizobium-Azospirillum* coinoculation on nitrogen fixation and yield of two contrasting *Phaseolus vulgaris* L. genotypes cultivated across different environments in Cuba. Plant Soil 312:25–37

Roberts IN, Caputo C, Criado MV, Funk C (2012) Senescence-associated proteases in plants. Physiol Plant 145:130–139. https://doi.org/10.1111/j.1399-3054.2012.01574.x

Roche P, Debelle F, Maillet F, Lerouge P, Faucher C, Truchet G, Denarie J, Prome JC (1991) Molecular basis of symbiotic host specificity in *Rhizobium meliloti*: nodH and nodPQ genes encode the sulfation of lipo-oligosaccharide signals. Cell 67:1131–1143

Rochester IJ (2007) Nutrient uptake and export from an Australian cotton field. Nutr Cycl Agroecosyst 77(3):213–223

Rogel MA, Hernandez-Lucas I, Kuykendall D, Balkwill DL, Martinez-Romero E (2001) Nitrogen-fixing nodules with *Ensifer adhaerens* harboring *Rhizobium tropici* symbiotic plasmids. Appl Environ Microbiol 67:3264–3268

Rolfe BG, Bender GL (1991) Evolving a *Rhizobium* for non-legume nodulation. In: Gresshoff PM, Roth LE, Stacey G, Newton WE (eds) Nitrogen fixation: achievements and objectives. Chapman and Hall, New York, pp 779–780

Romdhane SB, Trabelsi M, Aouani ME, de Lajudie P, Mhamdi R (2009) The diversity of rhizobia nodulating chickpea (*Cicer arietinum*) under water deficiency as a source of more efficient inoculants. Soil Biol Biochem 41:2568–2572

Ronson CW, Bosworth A, Genova M, Gudbrandsen S, Hankinson T, Kwaitowski R, Ratcliffe H, Robie C, Sweeney P, Szeto W, Williams M, Zablotowicz R (1990) Field release of genetically engineered *Rhizobium meliloti* and *Bradyrhizobium japonicum* strains. In: Gresshoff PM, Roth LE, Stacey G, Newton WE (eds) Nitrogen fixation: achievements and objectives. Chapman and Hall, New York, pp 397–403

Roth LE, Stacey G (1989a) Bacterium release into host cells of nitrogen-fixing nodules: the symbiosome membrane comes from three sources. Eur J Cell Biol 49:13–23

Roth LE, Stacey G (1989b) Cytoplasmic membrane systems involved in bacterium release into soybean nodule cells as studied with two *Bradyrhizobium japonicum* mutant strains. Eur J Cell Biol 49:24–32

Russelle MP, Schepers JS, Raun WR (2008) Biological dinitrogen fixation in agriculture. Agronomy 49:281–359

Sabry SRS, Saleh SA, Batchelor CA, Davey MR (1997) In: Xanfu V, Kennedy IR, Tinagwei C (eds) Biological nitrogen fixation, novel association with nonleguminous crops. Qungdao Ocean University Press, China, p 59

Sadowsky MJ, Cregan PB, Gottfert M, Sharma A, Gerhold D, Rodriquez-Quinones F, Keyser HH, Hennecke H, Stacey G (1991) The *Bradyrhizobium japonicum* nolA gene and its involvement in the genotype-specific nodulation of soybeans. Proc Natl Acad Sci U S A 88:637–641

Sadowsky MJ, Kosslak RM, Madrzak CJ, Golinska B, Cregan PB (1995) Restriction of nodulation by *Bradyrhizobium japonicum* is mediated by factors present in the root of *Glycine max*. Appl Environ Microbiol 61:832–836

Sahasrabudhe MM (2011) Screening of rhizobia for indole acetic acid production. Ann Biol Res 2(4):460–468

Saıdi S, Chebil S, Gtari M, Mhamdi R (2013) Characterization of root-nodule bacteria isolated from *Vicia faba* and selection of plant growth promoting isolates. World J Microbiol Biotechnol 29:1099–1106

Saikia J, Sarma RK, Dhandia R, Yadav A, Bharali R, Gupta VK, Saikia R (2018) Alleviation of drought stress in pulse crops with ACC deaminase producing rhizobacteria isolated from acidic soil of Northeast India. Sci Rep 8:3560. https://doi.org/10.1038/s41598-018-21921-w

Saini P, Khanna V (2012) Evaluation of native rhizobacteria as promoters of plant growth for increased yield in lentil (*Lens culinaris*). Rec Res Sci Technol 4(4):5–9

Saini I, Sindhu SS, Dadarwal KR (1996) Uptake hydrogenase, nitrate Respiration, *ex planta* nitrogenase expression and symbiotic effectivity of *Sesbania* rhizobia. Indian J Microbiol 36:93–97

Sanjuan J, Olivares J (1989) Implication of nifA in regulation of genes located on a *Rhizobium meliloti* cryptic plasmid that affect nodulation efficiency. J Bacteriol 171:4154–4161

Sanjuan J, Olivares J (1991a) Multicopy plasmids carrying the *Klebsiella pneumoniae* nifA gene enhances *Rhizobium meliloti* nodulation competitiveness on alfalfa. Mol Plant Microbe Interact 4:365–369

Sanjuan J, Olivares J (1991b) NifA-NtrA regulatory system activates transcription of nfe, a gene locus involved in nodulation competitiveness of *Rhizobium meliloti*. Arch Microbiol 155:543–548

Sassi-Aydi S, Aydi S, Abdelly C (2012) Inoculation with the native *Rhizobium gallicum* 8a3 improves osmotic stress tolerance in common bean drought-sensitive cultivar. Acta Agric Scand Sect B Soil Plant Sci 62:179–187

Sato T, Yashima H, Ohtake N, Sueyoshi K, Akao S, Ohyama T (1999) Possible involvement of photosynthetic supply in changes of nodule characteristics of hypernodulating soybeans. Soil Sci Plant Nutr 45:187–196

Saur I, Oakes M, Djordjevic MA, Imin N (2011) Crosstalk between the nodulation signaling pathway and the autoregulation of nodulation in *Medicago truncatula*. New Phytol 190:865–874

Sawada H, Kuykendall LD, Young JM (2003) Changing concepts in the systematics of bacterial nitrogen-fixing legume symbionts. J Gen Appl Microbiol 49:155–179

Schlindwein G, Vargas LK, Lisboa BB, Azambuja AC, Granada CE, Gabiatti NC, Prates F, Stumpf R (2008) Influence of rhizobial inoculation on seedling vigor and germination of lettuce. Ciencia Rural 38:658–664

Schmidt JE, Weese DJ, Lau JA (2017) Long-term agricultural management does not alter the evolution of a soybean–*Rhizobium* mutualism. Ecol Appl 27(8):2487–2496

Schofield PR, Ridge RW, Rolfe BG, Shine J, Watson JM (1984) Host-specific nodulation is encloded on a 14 kb fragment in *Rhizobium trifolii*. Plant Mol Biol 3:3–11

Schwedock J, Long SR (1992) *Rhizobium meliloti* genes involved in sulfate activation - The two copies of nod PQ and a new locus, saa. Genetics 132:899–909

Schwenke GD, Herridge DF, Scheer C, Rowlings DW, Haigh BM, McMullen KG (2015) Soil N_2O emissions under N_2-fixing legumes and N-fertilised canola: a reappraisal of emissions factor calculations. Agric Ecosyst Environ 202:232–242

Selvakumar G, Panneerselvam P, Ganeshamurthy AN (2012) Bacterial mediated alleviation of abiotic stress in crops. In: Bacteria in agrobiology: stress management. Springer, Berlin/Heidelberg, pp 205–224

Senbayram M, Wenthe C, Lingner A, Isselstein J, Steinmann H, Kaya C, Köbke S (2016) Legume-based mixed intercropping systems may lower agricultural born N_2O emissions. Energy Sustain Soc 6:2

Sessitsch A, Howieson JG, Perret X, Antoun H (2002) Advances in *Rhizobium* research. Crit Rev Plant Sci 21:323–378. https://doi.org/10.1080/0735-260291044278

Shaharoona B, Arshad M, Zahir ZA (2006) Effect of plant growth promoting rhizobacteria containing ACC-deaminase on maize (*Zea mays* L.) growth under axenic conditions and on nodulation in mung bean. Lett Appl Microbiol 42:155–159

Shaharoona B, Jamro GM, Zahir ZA, Arshad M, Memon KS (2007) Effectiveness of various *Pseudomonas* spp. and *Burkholderia caryophylli* containing ACC-deaminase for improving growth and yield of wheat (*Triticum aestivum* I.). J Microbiol Biotechnol 17(8):1300

Shahzad SM, Khalid A, Arif MS, Riaz M, Ashraf M, Iqbal Z, Yasmeen T (2014) Coinoculation integrated with P-enriched compost improved nodulation and growth of chickpea (*Cicer arietinum* L.) under irrigated and rainfed farming systems. Biol Fertil Soils 50:1–12

Shantharam S, Mattoo AK (1997) Enhancing biological nitrogen fixation: an appraisal of current and alternative technologies for N input into plants. Plant Soil 194:205–216

Sharma R, Sindhu S, Sindhu SS (2018a) Bioinoculation of mustard (*Brassica juncea* L.) with beneficial rhizobacteria: a sustainable alternative to improve crop growth. Intern J Curr Microbiol Appl Sci 7(5):1375–1386

Sharma R, Sindhu S, Sindhu SS (2018b) Suppression of Alternaria blight disease and plant growth promotion of mustard (*Brassica juncea* L.) by antagonistic rhizosphere bacteria. Appl Soil Ecol 129:145–150

Shiri-Janagard M, Raei Y, Gasemi-Golezani K, Aliasgarzard N (2012) Influence of *Bradyrhizobium japonicum* and phosphate solubilizing bacteria on soybean yield at different levels of nitrogen and phosphorus. Int J Agron Plant Prod 3(11):544–449

Sindhu SS, Dadarwal KR (1986) Ex planta nitorgenase induction and uptake hydrogenase in *Rhizobium* sp. (cowpea miscellany). Soil Biol Biochem 18(3):291–295

Sindhu SS, Dadarwal KR (1988) Effect of temperature on nitrogenase and hydrogenase activity in cowpea miscellany hosts. Indian J Microbiol 28(3):178–183

Sindhu SS, Dadarwal KR (1992) Symbiotic effectivity of cowpea miscellany *Rhizobium* mutants having increased hydrogenase activity. Indian J Microbiol 32:411–416

Sindhu SS, Dadarwal KR (1993) Broadening of host range infectivity in cowpea miscellany *Rhizobium* by protoplast fusion. Indian J Expt Biol 31:521–528

Sindhu SS, Dadarwal KR (1995a) Hydrogen uptake-measurement of photosynthate limitation in nodules of cowpea miscellany hosts. Microbiol Res 150:213–217

Sindhu SS, Dadarwal KR (1995b) Molecular biology of nodule development and nitrogen fixation in *Rhizobium*-legume symbiosis. In: Srivastava HS, Singh RP (eds) Nitrogen nutrition in higher plants. Associated Publishing Company, New Delhi, pp 57–129

Sindhu SS, Dadarwal KR (2000) Competition for nodulation among rhizobia in legume-*Rhizobium* symbiosis. Indian J Microbiol 40(4):211–246

Sindhu SS, Dadarwal KR (2001a) Chitinolytic and cellulolytic *Pseudomonas* sp. antagonistic to fungal pathogens enhances nodulation by *Mesorhizobium* sp. *Cicer* in chickpea. Microbiol Res 156(4):353–358

Sindhu SS, Dadarwal KR (2001b) Genetic manipulation of rhizobia to improve nodulation and nitrogen fixation in legumes. In: Yadav AK, Motsara MR, Ray Choudhary S (eds) Recent advances in biofertilizer technology. Society for Promotion and Utilization of Resources and Technology, New Delhi, pp 1–97

Sindhu SS, Dadarwal KR (2001c) Symbiotic effectiveness of spontaneous antibiotic-resistant mutants of *Rhizobium* sp. *Cicer* nodulating chickpea (*Cicer arietinum*). Microbiol Res 155:325–329. http://www.urbanfischer.de/journals/microbiolres

Sindhu SS, Lakshminarayana K (1982) Survival and competitive ability of ammonia excreting and non-ammonia excreting *Azotobacter chroococcum* strains in sterile soil. Plant Soil 69:79–84

Sindhu SS, Lakshminarayana K, Singh D (1994) Expression of hydrogenase activity in *Azotobacter chroococcum* and its possible role in crop productivity. Indian J Expt Biol 32:423–426

Sindhu SS, Gupta SK, Dadarwal KR (1999a) Antagonistic effect of *Pseudomonas* spp. on pathogenic fungi and enhancement of growth of green gram (*Vigna radiata*). Biol Fertil Soils 29:62–68

Sindhu SS, Mor S, Dadarwal KR (1999b) Cell surface polysaccharides of *Rhizobium* and nodule development on legume roots: recent advances. In: Gakhar SK, Mishra SN (eds) Recent trends in developmental biology. Himalaya Publishing House, New Delhi, pp 204–240

Sindhu SS, Gupta SK, Suneja S, Dadarwal KR (2002a) Enhancement of green gram nodulation and plant growth by *Bacillus* species. Biol Plant 45:117–120

Sindhu SS, Suneja S, Goel AK, Parmar N, Dadarwal KR (2002b) Plant growth promoting effects of *Pseudomonas* sp. on coinoculation with *Mesorhizobium* sp. *Cicer* strain under sterile and "wilt sick" soil conditions. Appl Soil Ecol 19:57–64

Sindhu SS, Sharma HR, Dadarwal KR (2003) Competition among *Bradyrhizobium* strains for nodulation of green gram (*Vigna radiata*): use of dark-nodule strain. Folia Microbiol 48(1):83–90

Sindhu SS, Parmar P, Phour M (2014) Nutrient cycling: potassium solubilization by microorganisms and improvement of crop growth. In: Geomicrobiol biogeochem. Springer, Berlin/Heidelberg, pp 175–198

Sindhu SS, Sehrawat A, Sharma R, Dahiya A (2016) Biopesticides: use of rhizosphere bacteria for biological control of plant pathogens. Defence Life Sci J 1:135–148

Sindhu SS, Sehrawat A, Sharma R, Dahiya A, Khandelwal A (2017) Belowground microbial cross-talk and rhizosphere Biology. In: Plant-microbe interactions in agro-ecological perspectives. Springer, Singapore, pp 695–752

Sindhu SS, Khandelwal A, Phour M, Sehrawat A (2018) Bioherbicidal potential of rhizosphere microorganisms for ecofriendly weed management. In: Role of rhizospheric microbes in soil. Springer, Singapore, pp 331–376

Singh G, Sekhon H, Sharma P (2011) Effect of irrigation and biofertilizer on water use, nodulation, growth and yield of chickpea (*Cicer arietinum* L.). Arch Agron Soil Sci 57:715–726

Sitrit Y, Barak Z, Kapulnik Y, Oppenheim AB, Chet I (1993) Expression of *Serratia marcescens* chitinase gene in *Rhizobium meliloti* during symbiosis on alfalfa roots. Mol Plant Microbe Interact 6:293–298

Sloger C, van Berkum P, Dutta SK (1992) Approaches for enhancing nitrogen fixation in cereal crops. Biological nitrogen fixation associated with rice production. In: Dutta SK, Sloger C (eds), pp 229–234

Smit G, Kijne JW, Lugtenberg BJJ (1987) Involvement of both cellulose fibrils and Ca^{2+} dependent adhesion in the attachment of *Rhizobium leguminosarum* to pea root hair tips. J Bacteriol 169:4294–4301

Smit P, Raedts J, Portyanko V, Debellé F, Gough C, Bisseling T, Geurts R (2005) NSP1 of the GRAS protein family is essential for rhizobial Nod factor-induced transcription. Science 308:1789–1791

Smith SR, Giller KE (1992) Effective *Rhizobium leguminosarum* biovar *trifolii* present in five soils contaminated with heavy metals from long-term applications of sewage sludge or metal mine spoil. Soil Biol Biochem 24(8):781–788

So RB, Ladha JK, Young JP (1994) Photosynthetic symbionts of *Aeschynomene* spp. forms a cluster with bradyrhizobia on the basis of fatty acid and rRNA analyses. Int J Syst Evol Microbiol 44(3):392–403

Soedarjo M, Borthakur D (1998) Mimosine, a toxin produced by the tree-legume *Leucaena* provides a nodulation competition advantage to mimosine-degrading *Rhizobium* strains. Soil Biol Biochem 30:1605–1613. https://doi.org/10.1016/S0038-0717(97)00180-6

Soedarjo M, Hemscheidt TK, Borthakur D (1995) Mimosine, a toxin present in leguminous trees (*Leucaena* spp.), induces a mimosine-degrading enzyme activity in some strains of *Rhizobium*. Appl Environ Microbiol 60:4268–4272

Solano BR, Maicas JB, FJG M (2008) Physiological and molecular mechanisms of plant growth promoting rhizobacteria (PGPR). In: Ahmad I, Pichtel J, Hayat S (eds) Plant-bacteria interactions: Strategies and techniques to promote plant growth. Wiley, Weinheim, pp 41–52

Somasegaran P, Bohlool BB (1990) Single strain versus multistrain inoculation: Effect of soil mineral N availability on rhizobial strain effectiveness and competition for nodulation on chickpea, soybean and dry bean. Plant Soil 170:351–358

Soto MJ, Zorzano A, Mercado-Blanco J, Lepek V, Olivares J, Toro N (1993) Nucleotide sequence and characterization of *Rhizobium meliloti* nodulation competitiveness genes *nfe*. J Mol Biol 229:570–579

Sougoufara B, Diem HG, Dommergues YR (1989) Response of field grown *Casuarina equisetifolia* to inoculation with *Frankia* strain ORS021001 entraped in alginate beads. Plant Soil 118:133–137

Soussana J-F, Tallec T, Blanfort V (2010) Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4(3):334–350

Souza V, Eguiarte L, Avila G, Cappello R, Gallardo C, Montoya J, Pinero D (1994) Genetic structure of Rhizobium etli biovar phaseoli associated with wild and cultivated bean plants (*Phaseolus vulgaris* and *Phaseolus coccineus*) in Morelos. Appl Environ Microbiol 60:1260–1268

Spaink HP (1996) Regulation of plant morphogenesis by lipo-chitinoligosaccharides. Crit Rev Plant Sci 15:559–582

Spaink HP, Okker RJH, Wijffelman CA, Tak T, Roo LG, Pees E, van Brussel AAN, Lugtenberg BJJ (1989) Symbiotic properties of rhizobia containing a flavonoid-independent hybrid nodD product. J Bacteriol 171:4045–4053

Sprent JI, Sprent P (1990) Nitrogen fixing organisms: pure and applied aspects. Chapman & Hall, London

Srinivasan M, Petersen DJ, Holl FB (1997) Nodulation of *Phaseolus vulgaris* by *Rhizobium etli* is enhanced in the presence of *Bacillus*. Can J Microbiol 43:1–8

Stacey G, Luka S, Sanjuan J, Banfalvi Z, Nieuwkoop AJ, Chun JY, Forsberg S, Carlson RW (1994) *nod*Z, a unique host-specific nodulation gene, is involved in the fucosylation of the lipo-oligosaccharide nodulation signal of *Bradyrhizobium japonicum*. J Bacteriol 176:620–633

Stajkovic O, Delic D, Josic D, Kuzmanovic D, Rasulic N, Knezevic-Vukcevic J (2011) Improvement of common bean growth by coinoculation with *Rhizobium* and plant growth-promoting bacteria. Rom Biotechnol Lett 16:5919–5926

Stevenson FJ (1982) Origin and distribution of nitrogen in soil. In: Stevenson FJ (ed) Nitrogen in agricultural soils, agronomy No. 22. American Society of Agronomy, Madison, pp 1–42

Strange RN, Scott PR (2005) Plant disease: a threat to global food security. Ann Rev Phytopathol 43:1–36

Sturtevant DB, Taller BJ (1989) Cytokinin production by *Bradyrhizobium japonicum*. Plant Physiol 89:1247–1252

Suárez R, Wong A, Ramírez M, Barraza A, Orozco MC, Cevallos MA, Lara M, Hernández G, Iturriaga G (2008) Improvement of drought tolerance and grain yield in common bean by overexpressing trehalose-6-phosphate synthase in rhizobia. Mol Plant Microbe Interact 21:958–966

Sullivan JT, Patrick HN, Lowther WL, Scott DB, Ronson CW (1995) Nodulating strains of *Rhizobium loti* arise through chromosomal symbiotic gene transfer in the environment. Proc Natl Acad Sci U S A 92:8985–8989

Suzuki A, Akune M, Kogiso M, Imagama Y, Osuki KI, Uchiumi T, Higashi S, Han SY, Yoshida S, Asami T, Abe M (2004) Control of nodule number by the phytohormone abscisic acid in the roots of two leguminous species. Plant Cell Physiol 45(7):914–922

Sy A, Giraud E, Samba R, Gillis M, Dreyfus B (2001) Nodulation of certain legumes of the genus *Crotalaria* by the new species *Methylobacterium*. Can J Microbiol 47(6):503–508

Szeto W, Kwiatkowski R, Cannon FC, Ronson CW (1990) The enhancement of symbiotic nitrogen fixation in *Bradyrhizobium japonicum*. In: Abstracts of fifth international symposium on the molecular genetics of plant-microbe interactions, Interlaken, Switzerland, p 152

Tairo EV, Ndakidemi PA (2013) *Bradyrhizobium japonicum* inoculation and phosphorus supplementation on growth and chlorophyll accumulation in soybean (*Glycine max* L.). Am J Plant Sci 4:2281–2289

Talano MA, Cejas RB, González PS, Agostini E (2013) Arsenic effect on the model crop symbiosis *Bradyrhizobium*-soybean. Plant Physiol Biochem 63:8–14

Tank N, Saraf M (2010) Salinity-resistant plant growth promoting rhizobacteria ameliorates sodium chloride stress on tomato plants. J Plant Interact 5:51–58

Tariq M, Hameed S, Yasmeen T, Ali A (2012) Non-rhizobial bacteria for improved nodulation and grain yield of mung bean [*Vigna radiata* (L.) Wilczek]. Afri J Biotechnol 11(84):15012–15019

Tate RL (1995) Soil microbiology (symbiotic nitrogen fixation). Wiley, New York

Tchan YT, Kennedy IR (1989) Possible nitrogen-fixing root nodules induced in non-legumes. Agric Sci 2:57–59

Tchebotar V, Kang U, Asis C Jr, Akao S (1998) The use of GUS-reporter gene to study the effect of *Azospirillum-Rhizobium* coinoculation on nodulation of white clover. Biol Fertil Soils 27:349–352

Tejera NA, Soussi M, Lluch C (2006) Physiological and nutritional indicators of tolerance to salinity in chickpea plants growing under symbiotic conditions. Environ Exp Bot 58:17–24

Thies JE, Singleton PW, Bohlool BB (1991) Influence of the size of indigenous rhizobial populations on establishment and symbiotic performance of introduced rhizobia on field-grown legumes. Appl Environ Microbiol 57(1):19–28

Timmers AC, Auriac MC, Truchet G (1999) Refined analysis of early symbiotic steps of the *Rhizobium-Medicago* interaction in relationship with microtubular cytoskeleton rearrangements. Development 126:3617–3628

Tominaga A, Nagata M, Futsuki K, Abe H, Uchiumi T, Abe M, Kucho KI, Hashiguchi M, Akashi R, Hirsch A, Arima S (2010) Effect of abscisic acid on symbiotic nitrogen fixation activity in the root nodules of *Lotus japonicus*. Plant Signal Behav 5(4):440–443

Trinick MJ, Hadobas PA (1995) Formation of nodular structures on the non-legumes *Brassica napus*, *B. campestris*, *B. juncea* and *Arabdiopsis thaliana* with *Bradyrhizobium* and *Rhizobium* isolated from *Parasponia* spp. or legumes grown in tropical soils. Plant Soil 172:207–219

Triplett EW (1988) Isolation of genes involved in nodulation competitiveness from *Rhizobium leguminosarum* bv. *trifolii* T24. Proc Natl Acad Sci U S A 85:3810–3814

Triplett EW (1990) Construction of a symbiotically effective strain of *Rhizobium leguminosarum* bv. *trifolii* with increased nodulation competitiveness. Appl Environ Microbiol 56:98–103

Truchet G, Rosenberg C, Vasse J, Julliot JS, Camut S, Denarie J (1984) Transfer of *Rhizobium meliloti* sym genes into *Agrobacterium tumefaciens*: host specific nodulation by a typical infection. J Bacteriol 157:134–142

Tu C, Teng Y, Luo Y, Li X, Sun X, Li Z, Liu W, Christie P (2011) Potential for biodegradation of polychlorinated biphenyls (PCBs) by *Sinorhizobium meliloti*. J Hazard Mater 186:1438–1444. https://doi.org/10.1016/j.jhazmat.2010.12.008

Turner JT, Backman PA (1991) Factors relating to peanut yield increased following *Bacillus subtilis* seed treatment. Plant Dis 75:347–353

Uma C, Sivagurunathan P, Sangeetha D (2013) Performance of bradyrhizobial isolates under drought conditions. Int J Curr Microbiol App Sci 2:228–232

Urban JE, Davis L, Brown SJ (1986) *Rhizobium trifolii* 0403 is capable of growth in the absence of combined nitrogen. Appl Environ Microbiol 52(5):1060–1067

Uribe AL, Winham DM, Wharton CM (2012) Community supported agriculture membership in Arizona. An exploratory study of food and sustainability behaviours. Appetite 59(2):431–436

van Elsas JD, Heijnen CE (1990) Methods for the introduction of bacteria into soil: a review. Biol Fertil Soils 10(2):127–133

van Veen JA, van Overbeek LS, van Elsas JD (1997) Fate and activity of microorganisms introduced into soil. Microbiol Mol Biol Rev 61:121–135

van Wyk SG, Du Plessis M, Cullis C, Kunert KJ, Vorster BJ (2014) Cysteine protease and cystatin expression and activity during soybean nodule development and senescence. BMC Plant Biol 14:294–307. https://doi.org/10.1186/s12870-014-0294-3

van Zeijl A, Op den Camp RH, Deinum EE, Charnikhova T, Franssen H, Op den Camp HJ, Bouwmeester H, Kohlen W, Bisseling T, Geurts R (2015) *Rhizobium* lipo-chitooligosaccharide signaling triggers accumulation of cytokinins in *Medicago truncatula* roots. Mol Plant 8:1213–1226

Valverde A, Araceli B, Tiziana F, Rivas R, Encarna R, Claudio V, Emilio R, Manual C, Jose-Mariano C (2006) Differential effects of inoculation with *Pseudomonas jessenii* PS06 and *Mesorhizobium ciceri* C-212 strain on the growth and seed yield of chickpea under greenhouse and field conditions. Plant Soil 287:43–50

Vande Velde W, Guerra JC, De Keyser A, De Rycke R, Rombauts S, Maunoury N, Mergaert P, Kondorosi E, Holsters M, Goormachtig S (2006) Aging in legume symbiosis. A molecular view on nodule senescence in *Medicago truncatula*. Plant Physiol 141:711–720. https://doi.org/10.1104/pp.106.078691

Vardhini BV, Ram Rao SS (1999) Effect of brassionosteriods on nodulation and nitrogenase activity in groundnut (*Arachis hypogaea* L.). Plant Growth Regul 28(3):165–167

Vargas LK, Lisboa BB, Schlindwein G, Granada CE, Giongo A, Beneduzi A, Passaglia LMP (2009) Occurrence of plant growth-promoting traits in clover-nodulating rhizobia strains isolated from different soils in Rio Grande do Sul state. R Bras Ci Solo 33:1227–1235

Varin S, Lemauviel-Lavenant S, Bernard-Cliquet J, Diquelou S, Padraic T, Mischaelson-Yeates T (2009) Functional plasticity of *Trifolium repens* L. in response to sulphur and nitrogen availability. Plant Soil 317:189–200. https://doi.org/10.1007/s11104-008-9800-4

Vasse J, de Billy F, Camut S, Truchet G (1990) Correlation between ultrastructural differentiation of bacteroids and nitrogen fixation in alfalfa nodules. J Bacteriol 172:4295–4306

Velázquez E, Martínez-Romero E, Rodríguez-Navarro DM, Trujillo ME, Daza A, Mateos PE, MartínezMolina E, van Berkum P (2001) Characterization of rhizobial isolates of *Phaseolus vulgaris* by staircase electrophoresis of low-molecular weight RNA. Appl Environ Microbiol 67:1008–1010

Venkateshwaran M, Volkening JD, Sussman MR, Ané JM (2013) Symbiosis and the social network of higher plants. Curr Opin Plant Biol 16(1):118–127

Verma JP, Yadav J, Tiwari KN, Kumar A (2013) Effect of indigenous *Mesorhizobium* spp. and plant growth promoting rhizobacteria on yields and nutrients uptake of chickpea (*Cicer arietinum* L.) under sustainable agriculture. Ecol Eng 51:282–286

Verma JP, Yadav J, Tiwari KN, Jaiswal DK (2014) Evaluation of plant growth promoting activities of microbial strains and their effect on growth and yield of chickpea (*Cicer arietinum* L.) in India. Soil Biol Biochem 70:33–37

Vidor C, Miller RH (1980) Relative saprophytic competence of *Rhizobium japonicum* strains in soils as determined by the quantitative fluorescent antibody (FA) technique. Soil Biol Biochem 12(5):483–487

Vineusa P, Léon-Barrios M, Silva C, Willems A, JabaroLorenzo A, Pérez-Galdona R, Werner D, MartínezRomero E (2005) *Bradyrhizobium canariense* sp. nov., an acid-tolerant endosymbiont that nodulates endemic genistoid legumes (Papilionoideae: Genisteae) from canary Islands, along with *Bradyrhizobium japonicum* bv. *genistearum*, *Bradyrhizobium* genospecies alpha and *Bradyrhizobium* genospecies beta. Int J Syst Evol Microbiol 55:569–575

Vlassak KM, Vanderleyden J, Franco A (1996) Competition and persistence of *Rhizobium tropici* and *R. etli* in tropical soil during successive bean (*Phaseolus vulgaris* L.) cultures. Biol Fertil Soils 21:61–66

Vriezen JAC, de Bruijn FJ, Nusslein K (2007) Responses of rhizobia to desiccation in relation to osmotic stress, oxygen and temperature. Appl Environ Microbiol 73:3451–3459

Waelkens F, Voets T, Vlassak K, Vanderleyden J, van Rhizn P (1995) The *nod*S gene of Rhizobium tropici CIAT899 is necessary for nodulation of *Phaseolus vulgaris* and *Leucaena leucocephala*. Mol Plant Microbe Interact 8:147–154

Walpola BC, Yoon M-H (2013) Isolation and characterization of phosphate solubilizing bacteria and their coinoculation efficiency on tomato plant growth and phosphorous uptake. Afr J Microbiol Res 7(3):266–275

Wang TL, Wood EA, Brewin NJ (1982) Growth regulators and nodulation in peas. The cytokinin content of a wild type and a Ti plasmid containing strain of *R. leguminosarum*. Planta 155:350–355

Wang ET, Rogel A, Santos AG, Martínez-Romero J, Cevallos MA, Martínez-Romero E (1999) *Rhizobium etli* bv *mimosae*, a novel biovar isolated from *Mimosa affinis*. Int J Syst Bacteriol 49:1479–1491

Wani PA, Khan MS (2013) Nickel detoxification and plant growth promotion by multi metal resistant plant growth promoting *Rhizobium* species RL9. Bull Environ Contam Toxicol 91:117–124

Wani SP, Rupela OP, Lee KK (1995) Sustainable agriculture in the semi-arid tropics through biological nitrogen fixation in grain legumes. Plant Soil 174:29–49

Wani PA, Khan MS, Zaidi A (2007a) Coinoculation of nitrogen fixing and phosphate solubilizing bacteria to promote growth, yield and nutrient uptake in chickpea. Acta Agron Hung 55:315–323

Wani PA, Khan MS, Zaidi A (2007b) Effect of metal tolerant plant growth promoting *Bradyrhizobium* sp. (*Vigna*) on growth, symbiosis, seed yield and metal uptake by green gram plants. Chemosphere 70:36–45

Wani PA, Khan MS, Zaidi A (2007c) Synergistic effects of the inoculation with nitrogen fixing and phosphate solubilizing rhizobacteria on the performance of field grown chickpea. J Plant Nutr Soil Sci 170:283–287

Wani PA, Khan MS, Zaidi A (2008) Chromium-reducing and plant growth promoting *Mesorhizobium* improves chickpea growth in chromium-amended soil. Biotechnol Lett 30:159–163

Webster G, Davey MR, Cocking EC (1995) *Parasponia* with rhizobia: a neglected non-legume nitrogen-fixing symbiosis. AgBiotech News Info 7:119N–124N

Webster G, Gough C, Vasse J, Batchelor CA, O'Callaghan KJ, Kothari SL, Davey MR (1997) Interactions of rhizobia with rice and wheat. Plant Soil 194:115–122

Werner D (2005) Production and biological nitrogen fixation of tropical legumes. In: Nitrogen fixation in agriculture, forestry, ecology and the environment. Springer, Dordrecht, pp 1–13

Williams MK, Beynon JL, Ronson CW, Cannon FC (1990) In: Abstracts of fifth international symposium on the molecular genetics of plant-microbe interactions. Interlaken, Switzerland, p 152
Wilson KJ, Peoples MB, Jefferson RA (1995) New techniques for studying competition by rhizobia and for assessing nitrogen fixation in the field. Plant Soil 174:241–253
Wittenberg JB, Wittenberg BA, Day DA, Udvardi MK, Appleby CA (1996) Siderophore bound iron in the peribacteroid space of soybean root nodules. Plant Soil 178:161–169
Woomer P, Singleton PW, Bohlool BB (1988) Ecological indicators of native rhizobia in tropical soils. Appl Environ Microbiol 54(5):1112–1116
Xiao TT, Schilderink S, Moling S, Deinum EE, Kondorosi E, Franssen H, Kulikova O, Niebel A, Bisseling T (2014) Fate map of *Medicago truncatula* root nodules. Development 141:3517–3528
Yadav A, Gaur I, Goel N, Mitra J, Saleem B, Goswami S, Paul PK, Upadhyaya KC (2015) Rhizospheric microbes are excellent plant growth promoters. Indian J Natur Sci 5(30):6584–6595
Yadegari M, Rahmani HA, Noormohammadi G, Ayneband A (2008) Evaluation of bean (*Phaseolus vulgaris*) seeds inoculation with *Rhizobium phaseoli* and plant growth promoting rhizobacteria on yield and yield components. Pak J Biol Sci PJBS 11(15):1935–1939
Yamato M, Nakayama Y, Yokoyama T, Ueno O, Akao S (1997) Nodulation of *Rhizobium fredii* USDA192 containing *Rhizobium leguminosarum* bv. *trifolii* ANU843 *nod* genes on homologous host soybean and heterologous host clover. Soil Sci Plant Nutr 43:51–61
Yang L, Tang R, Zhu J, Liu H, Mueller-Roeber B, Xia H, Zhang H (2008) Enhancement of stress tolerance in transgenic tobacco plants constitutively expressing AtIpk2β, an inositol polyphosphate 6-/3-kinase from *Arabidopsis thaliana*. Plant Mol Biol 66(4):329–343
Yang S, Tang F, Gao M, Krishnan HB, Zhu H (2010) R gene-controlled host specificity in the legume–rhizobia symbiosis. Proc Natl Acad Sci 107(43):18735–18740
Yasmeen T, Hameed S, Tariq M, Ali S (2012) Significance of arbuscular mycorrhizal and bacterial symbionts in a tripartite association with *Vigna radiate*. Acta Physiol Plant 34:1519–1528
Young JPW, Johnston AWB (1989) The evolution of specificity in the legume-*Rhizobium* symbiosis. Trends Ecol Evol 4:341–349
Yu X, Liu X, Zhu TH, Liu GH, Mao C (2012) Coinoculation with phosphate-solubilzing and nitrogen-fixing bacteria on solubilization of rock phosphate and their effect on growth promotion and nutrient uptake by walnut. Euro J Soil Biol 50:112–117
Zafar-ul-Hye M, Ahmad M, Shahzad SM (2013) Synergistic effect of rhizobia and plant growth promoting rhizobacteria on the growth and nodulation of lentil seedlings under axenic conditions. Soil Environ 32:79–86
Zahir ZA, Shah MK, Naveed M, Akhter MJ (2010) Substrate dependent auxin production by *Rhizobium phaseoli* improves the growth and yield of *Vigna radiata* L. under salt stress conditions. J Microbiol Biotechnol 20:1288–1294
Zahran HH (1999) *Rhizobium*-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. Microbiol Mol Biol Rev 63(4):968–989
Zhang XP, Karsisto M, Harper R, Lindstrom K (1991) Diversity of *Rhizobium* bacteria isolated from the root nodules of leguminous trees. Int J Syst Bacteriol 41:104–113
Zhang F, Dashti N, Hynes RK, Smith DL (1996) Plant growth promoting rhizobacteria and soybean {*Glycine max* (L.) Merr.} nodulation and nitrogen fixation at suboptimal root zone temperatures. Annals Bot 77:453–459
Zhang YHP, Himmel ME, Mielenz JR (2006) Outlook for cellulase improvement: screening and selection strategies. Biotechnol Adv 24(5):452–481

Sustainable Soil Management Practices in Olive Groves

8

Victor Kavvadias and Georgios Koubouris

Abstract

Olive (*Olea europaea* L.) is a common cultivated tree crop in the Mediterranean Basin. Inappropriate cultivation practices (i.e. excessive tillage and application of herbicides, the absence of organic amendments, the burning of pruning residues in situ) lead, in combination with the Mediterranean climate, to the depletion of soil organic matter, erosion, desertification and degradation of water resources. Strategies based on changes in the land management (e.g. cover crops and green manure, restriction of tillage, recycling of agricultural wastes and pruning residues), have been reported to enhance soil structure, increase soil fertility, decrease soil erosion, increase the C stored in soil, and reduce atmospheric CO_2. This chapter highlights soil management techniques that could promote the conservation of the productive olive grove system and thus contribute to the sustainability of the natural resources. During olive tree growth and olive oil production a large quantity of plant residues and mill wastes are produced. The implementation of alternative olive cultivation techniques (reduced/no tillage, plant residue and weed management, tree pruning, etc.) has not been systematically tested under the prevailing conditions of the Mediterranean olive forest. Although there are multiple specific studies taking into account specific practices in selected regions, a holistic approach for the Mediterranean olive groves has not yet been known. The design, the development and the adoption of

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an integrated soil management system in olive groves, adjustable to local soil climatic conditions is proposed, among further research priorities.

Keywords
Olive · Soil management · Residue management · Cover crops · Tillage

8.1 Introduction

The sustainability of agroecosystems is a key prerequisite for the sustainable development of human society as a whole. Soil quality is an ideal indicator of sustainability in the overall ecosystem functioning. There are many factors that may limit crop growth such as low soil depth, poor soil structure, salinity, alkalinity and stoniness that aggravate the drought conditions. The main environmental problem in the Mediterranean area is soil degradation by soil erosion due to low vegetation cover, high rainfall intensity, improper crop management and over-grazing (CEC 1992; Yassoglou 1971). Indeed, Cerdà et al. (2010) noted that due to the low addition of carbon from plant residues and to congenital tillage management Mediterranean soils have low organic matter content and medium to poor fertility. Soil content in organic carbon is below 1.0% to 1.5% in several areas of south Greece, Spain i.e. reaching the limit for irreversible desertification process. In agricultural cropping systems, the largest part of carbon is stored inside the soil (Freibauer et al. 2004). Organic matter plays a key role in soil quality and its maintenance to an adequate level is a critical task. In fact, organic matter supports the decomposition process that supplies mineral nutrients to plants, improves soil structure and water holding capacity (Abiven et al. 2009), increases the natural suppressiveness against soil-borne pathogens (Bonanomi et al. 2010) and reduces heavy metal toxicity (Park et al. 2011).

Croplands worldwide could sequester between 0.90 and 1.85 Pg C/yr. (1 Pg = 10^{15} g) (Zomer et al. 2017). It is thus crucial to have a good knowledge of the current SOC content and forms (labile, slow cycling, recalcitrant) and its spatial distribution, so as to inform various stakeholders (e.g. farmers, policy makers, land users) to make the best use of the available land and provide the best opportunities to mitigate and adapt to climate changes. Most of Med EU countries show a limited adoption of SOC management practices (Sánchez et al. 2016). Both types of practices that reduce soil disturbance and favor the soil aggregate stabilization are seldom used. For example, in Southern Spain reduced tillage is implemented in no more than the 20% of arable land and zero tillage represents only 7%, while in central eastern Italy residue management and cover crops are adopted on less than the 20% of land (Merante et al. 2017). In fact, the extent to which target groups are aware of practices that contribute to improved soil carbon and the regional understanding of the effective choices and costs varies considerably across the Mediterranean regions (Sánchez et al. 2014).

Olive (*Olea europaea* L.) is a widely cultivated tree crop in the Mediterranean region. It has been cultivated for centuries mainly in the hilly and marginal parts of the Mediterranean Basin. It is of high importance as olive groves under different soil climatic conditions have a key role in the preservation of the green landscape, the prevention of soil erosion and land degradation. Ben Ahmed et al. (2009) noted that olive tree is the most extended crop in the arid areas of Tunisia, not only due to its socioeconomic importance and the health benefits of olive oil consumption, but also thanks to its tolerance to contrasting environmental conditions (high temperature, low precipitation, high photosynthetic photon flux density, water and salt stresses).

About 70% of the olive orchards in the world have traditionally low productivity, mainly due to the lack of appropriate management systems. Inappropriate cultivation practices (i.e. excessive tillage, weed control by tillage and chemical treatment, the absence of organic amendments, burning of pruning residues in situ), in combination with the Mediterranean climate, lead to depletion of soil organic matter, erosion, biodiversity losses, desertification, soil salinization, groundwater contamination and degradation of water resources (Ben-Gal 2011; Benitez et al. 2006; Fernández-Escobar et al. 2012; Palese et al. 2013).

Nieto et al. (2011) pointed out that, in olive orchards of South Spain, tillage or no-tillage practices with bare soil reduce the incorporation of plant residues into the soil, thus changing the quantity of soil organic carbon and accelerating soil erosion (Pastor 2004). In addition, conventional tillage practices can damage the roots of trees leading to a substantial loss of carbohydrates. Additionally, conventional tillage practices increase the mineralization of SOC and favor soil respiration (Balesdent et al. 2000). Martínez-Mena et al. (2008) found that the losses associated with erosive events can reach up to 5.12 g C cm^{-1} in 15 months representing a significant proportion of the SOC lost in a semiarid area of South-East Spain.

The conservation of the productive olive grove system contributes to the sustainability of the natural resources. Olives maintained the productive possibility in the barren and dry Mediterranean soils, with very high erosion levels. Olive trees are drought resistant and thanks to their extensive rooting system they are among the few crops that can survive in only 200–300 mm of annual rainfall (Fresco 1996). The importance of olive cultivation is becoming even more important considering the fact that the olive grove exploits marginal productivity in inclining soils that are under an increased danger of deterioration (de Graaff and Eppink 1999).

The intensively cultivated orchards may have suitable productivity but are often associated with adverse environmental impacts (Metzidakis et al. 2008). In the semiarid Mediterranean olive orchards, the loss of soil fertility needs to be avoided by using innovative and optimized agricultural techniques with low environmental impact (Rewald et al. 2011; Gucci et al. 2012). In recent years, the use of cultivation systems that might be able to improve or preserve soil quality, health and fertility in olive orchards is highly recommended. Many authors have reported that the optimization and innovative use of soil conservative practices have positive effects on both crop yield and soil quality, as not only do they increase carbon sequestration by the soil but also reduce the atmospheric CO_2 concentration (Jarecki and Lal 2003; Hernández et al. 2005; Smith et al. 2008), while alongside they increase microbial biomass activity and complexity (Gruhn et al. 2000; Kushwaha et al. 2000; Widmer et al. 2006). The adoption of alternative land management practices on soil properties, such as conservation tillage or no tillage, promote natural resources conservation and the productivity of olive groves (Metzidakis et al. 2012).

The reduction of the environmental impact in olive groves is associated with the presence of SOM that relates to soil organic carbon. By conserving and enhancing SOC we can increase the amount of carbon sequestered in soils and improve soil quality (Brevik 2012). The common problem of the soil organic carbon loss worldwide could be reversed by the implementation of soil management techniques that can help the mitigation of climate change. By fixing CO_2 as soil organic matter, its nutrient retention capacity increases and the same applies to water retention. The latter is of paramount importance and urgency as an adaptation measure to the threatened increase of temperature in the arid and semiarid regions of the Mediterranean basin where olive trees, been evergreen, are invaluable to protect soil from erosion and the subsequent threat of desertification. Indeed, Freibauer et al. (2004) concluded that the carbon stock–enhancing effect of SOC management practices can occur either because of increased carbon input (cover crops, crop rotation, residue management) or reduced soil disturbance (reduced tillage, zero tillage, direct drilling), or through a combination of the two (Merante et al. 2017).

Therefore an improved knowledge of management factors affecting soil quality is crucial to plan soil management systems that effectively maintain soil fertility (Scotti et al. 2015). Main soil management techniques implemented in olive groves are reviewed below.

8.2 Residue Management

Crop residue management has a very important focus of concern among various stakeholders. Typical questions from farmers are how to manage the straw and stubble, the amount to be retained, the risk of disease spread and wildfire and when to remove the excess crop residues. Some areas face an excess of crop residues and the allelopathic problems that are observed have not been well described and analysed. Other areas suffer from a lack of sufficient mulch and even livestock grazing, feeding and bedding compete for straw and stubble.

One of the most important soil management strategies that aim to increase the carbon pool in soil is the addition of organic matter. Mulch using plant residues is becoming increasingly popular to farmers, also because it reduces both the need for weed control measures (Calatrava and Franco 2011) and soil and nutrient losses (Rodríguez-Lizana et al. 2008), while it increases soil moisture (Lozano-García et al. 2011). Mulching helps to ensure partial weed control because when the mulch decomposes, it forms a physical barrier and produces allelopathic substances (IOOC 2007). Mulch improves the key factors that contribute to crop production, i.e. it increases yields, it promotes crop growth and it reduces weed growth (Ramakrishna et al. 2006; Farzi et al. 2017). Moreover, in recent years mulching has become one of the best practices to increase the irrigation efficiency and to enhance the efficient use of rainfall by crops in arid and semi-arid areas (Farzi et al. 2017). In addition, Farzi et al. (2017) concluded that mulching treatments, especially de-oiled olive pomace mulch and pistachio shell mulch, significantly alleviated water-deficit stress in olive plants. The high soil water content under mulch cover encourages optimal transpiration, the nutrient uptake and the rate of photosynthesis required for plant growth. Additionally, soil cover with straw mulch or green manure decreased nitrate–N loss from top soil in a winter wheat-summer fallow system on dry land (He et al. 2015).

In most Mediterranean countries olive trees are a major source of agricultural residues. The impact of different soil-management systems on soil properties has been studied for olive orchards (e.g. Hernández et al. 2005; Soria et al. 2005; Castro et al. 2008; Gómez et al. 2009a), but a few works have evaluated the effect of shredded olive-tree pruning residues (Sofo et al. 2005; Rodríguez-Lizana et al. 2008; Koubouris et al. 2017; Kourgialas et al. 2017; Bechara et al. 2018; Kavvadias et al. 2018a, b, c) and have provided quantitative data on the amount of olive organic residues (Ordóñez-Fernández et al. 2015). Strategies based on changes in the management of organic amendments have been reported to increase the C stored in soil, to enhance soil structure, to increase soil fertility, to decrease soil erosion and to reduce atmospheric CO_2 (Sánchez-Monedero et al. 2008; Gómez et al. 2009a; Russo et al. 2015). Actually, spreading the shredded pruning debris material over the olive orchard is becoming a preferable alternative to burning. The sustainable management of olive tree pruning residue can positively affect soil moisture, nitrogen and carbon dynamics in soils (Arampatzis et al. 2018; Gómez-Muñoz et al. 2016). Covering soil with vegetation residues contributes to protection from erosion, increase rainfall water infiltration and carbon storage (Xiloyannis et al. 2016). Ordóñez-Fernández et al. (2015) reported that the application of pruning residues confirmed a greater improvement in soil fertility compared to the soil covered by spontaneous weeds, which is the option most frequently adopted by organic olive growers in terms of improvement in N, P and K soil content. In addition, the largest amount of fine pruning residues was the most efficient in terms of improving soil fertility.

The residues left from fruit cleaning in the oil mill, composed of leaves, green twigs, can also be spread on the soil surface, returning to the soil the elements previously taken up by the tree. Nieto et al. (2011) showed that the application of shredded olive-pruning residues and the plant residues from olive-fruit cleaning increased the uppermost 10 cm organic fraction in soil types (Chromic Calcisols and Calcic Vertisols) with respect to the tillage soils. The SOC content was greater in the Chromic Calcisols, where these soils were subjected to a longer time period of soil management. Exchangeable K^+ content, CEC and water-storage capacity were also increased, improving the soil quality.

The main techniques for recycling pruning residue are through a) chipper shredder and b) tractor mounted flail lawn mower (Fig. 8.1, oLIVE-CLIMA; LIFE 11/ENV/000942). In the case of chipper shredder, smaller and more uniform pieces of wood are produced resulting in faster decomposition rate, faster nutrient recycling and short term carbon storage. In contrast, flail lawn mower produces large and

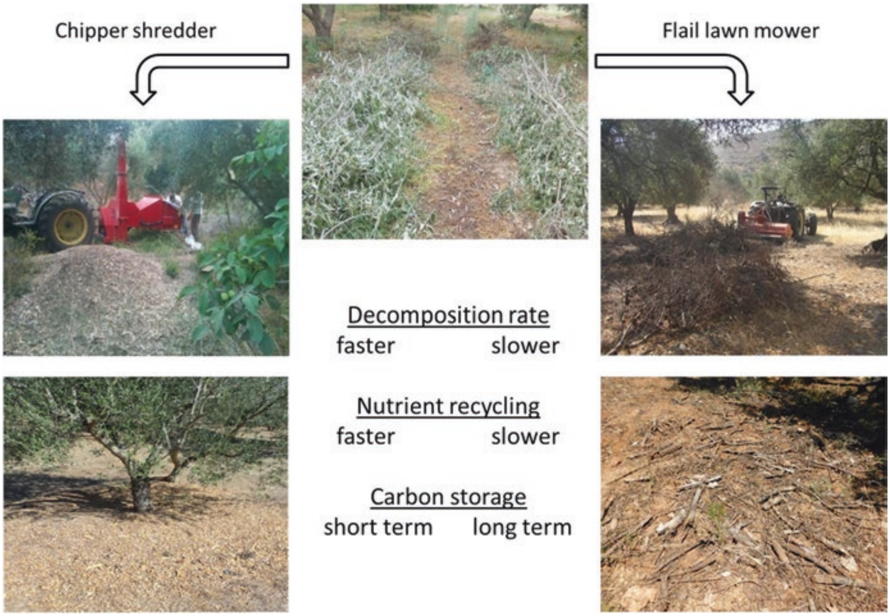

Fig. 8.1 Recycling pruning residue: the main techniques for recycling pruning residue are through (**a**) chipper shredder and (**b**) tractor mounted flail lawn mower

variable wood pieces that decompose slower but would contribute to long term carbon storage. Several other disadvantages i.e. damages in the fruit harvesting carpets, risk of increase in insect populations feeding on the wood as well as degradation in terms of orchard aesthetics, would discourage farmers to use flail lawn mower. However in terms of cost, flail lawn mower is much cheaper to operate because it requires only the driver and no additional workers to feed the machine. It is evident that the cultivation of olive trees produces a large quantity of biomass, such as branches of different thickness and leaves. At the same time high loads of both liquid and solid olive mill wastes are being produced during the procedures of olive oil's extraction (Calatrava and Franco 2011; Koubouris et al. 2017; Kavvadias et al. 2018a). Thus it is necessary to introduce the appropriate practices in soil management and to initiate changes in policy for treating olive residues as by-product in line with the Circular Economy (EC 2015). Regarding crop health safety, Markakis et al. (2017) suggested low risk of pathogen dispersion in the fields when good agricultural practices and regular orchard monitoring are carried out while residue from diseased trees should be burned the soonest.

8.3 Use of Compost as Organic Input

Compost is the product of organic wastes' decomposition. The use of compost as organic amendment allows for the reducing of the costs of green/urban waste disposal, the recycling of nutrient elements for crops N, P K and Mg and providing soil organic matter and an increase in microbial activity (Donn et al. 2014; Scotti et al. 2015), suppressing soil borne pathogens (Borrero et al. 2004). Positive effects of compost amendment on nutrient elements recycling and soil fertility are obvious through intense vegetative weed growth around the trees where compost was applied (Fig. 8.2, oLIVE-CLIMA; LIFE 11/ENV/000942). One of the most important factors affecting soil fertility in olive groves is the input of organic matter as compost to soil, because it increases soil permeability and water retention, promotes better availability of nutrients for plants, higher CO_2 uptake and carbon fixation, and reduces soil erosion (Toscano et al. 2009; Casacchia et al. 2012; Diacono and Montemurro 2010). Olive tree pruning and leaves after shredding have been used as a bulking agent for composting with other organic residues with encouraging results (Manios 2004). Casacchia et al. (2012) performed a two-year experiment with two different soils from an olive orchard, one managed traditionally and the other amended with in situ produced compost. The authors found increases in total organic matter and total nitrogen and pH in the amended soil compared to that managed traditionally. Furthermore, significant increases in total and specific microbial counts were noted in the amended soil with a clear amelioration of microbiological soil quality.

Fig. 8.2 Compost amendment improves soil fertility: positive effects of compost amendments on nutrient elements recycling and soil fertility are obvious through intense vegetative weed growth around the trees where compost was applied

The continuous application of composted olive mill wastes to the olive grove can represent an efficient strategy to increase both soil fertility and C sequestration. Regni et al. (2017) evaluated the long term effect of fresh olive pomace deriving from a three-phase oil extraction system (SOMW) or composted mixture of SOMW and shredded olive tree pruning residue (C-SOMW+P) on the vegetative and productive activities of olive trees, on the C stored in the tree non-permanent structures (prunings and fruits) and in the soil. Their results showed that about 50% of the C supplied by the treatment with C-SOMW+P was sequestered in the olive grove system, with more than 90% of the sequestered C stored inside the soil. The low amount of C sequestered in the soil following the addition of SOMW was attributed to its richness in moisture and easily degradable compounds that triggered the mineralization processes controlled by the soil microbial community. Montanaro et al. (2012) reported that when the long term application of chipped tree pruning residues was combined with the application of compost in soil in Mediterranean tree crops, then organic matter substantially increased.

Recycling of plant residue biomass combined with compost addition for many years increased soil organic carbon in other Mediterranean tree crops such as peach, kiwifruit and apricot (Montanaro et al. 2010, 2012). Soil amendment using composts derived by olive mill by-products can be an important agricultural practice for supporting and stimulating soil microorganisms and, at the same time, for reusing the by-products, thus avoiding their negative environmental impact (Bechara et al. 2018). However, in some soils with high initial SOC levels, the absence or decrease of SOC cannot be detected. Merante et al. (2017) and Koubouris et al. (2017) emphasized the fact that an adoption of practices to increase SOM should be implemented with special care to protect existing soil aggregates and meet soil carbon storage potential. Mediterranean soils are generally characterized by low C and clay contents (Merante et al. 2017) and therefore C storage capacity is limited and soil may be already saturated with C even with SOC as low as 1% (Dexter et al. 2008; Koubouris et al. 2017). Over the long term, the carbon sequestration following the application of olive organic residues was higher in soils with greater quantities of clay (Nieto et al. 2011).

Kavvadias et al. (2018b) reported that organic matter additions such as compost from shredded pruning residues or olive mill by-products did not have a significant effect on SOM, total and inorganic nitrogen and soil microbial properties. This was attributed to the relatively low amount of organic materials applied to soil parcels each year and the addition of fresh organic matter, which was poor in nutrients and thus could result in poor response of the microbial biomass to form new biomass. Rui et al. (2016) noticed that the difficulty in increasing soil C by crop residue input may be related to the decrease of microbial carbon use efficiency. The response of the soil microbial biomass may not be substantial, due to insufficient inorganic nutrients to form new biomass. Ferrara et al. (2015) and Jokela et al. (2009) registered limited changes in SOM and other chemical parameters after a soil amendment with various organic materials. They concluded that it may take many years before some soil quality indicators fully respond.

It should be noted that the 'in farm" method of compost production needs limited resources and low energetic inputs and uses machinery and equipment often already present at the farm. Indeed, to be really sustainable, the composting process should be carried out using the by-products available in situ. Sofo et al. (2014) suggested that studies need to be performed to evaluate whether mixtures of olive mill wastes, and olive pruning residues, can be efficiently composted under "in farm," nonindustrial conditions.

8.4 Cover Crops and Green Manure

Cover crops constitute one of the leading agro-environmental trends in Mediterranean olive-grove cultivation. The prime objectives of green manure and cover crop are protection against soil degradation and soil erosion caused by rain and wind and the raise of nitrogen content and that of SOM, especially in the upper layers (Gómez et al. 2009b; Ramos et al. 2010; Goss et al. 2013). Therefore, the mineral nitrogen available for olive growth rises (Wells et al. 2000), but there is also an increase in microbial activity and water retention capability (Scotti et al. 2015). Green manure improves the nutrition of the consecutive crop (Dabney et al. 2010) and soil physical conditions (Alliaume et al. 2014). In Mediterranean conditions, cover crops are established during autumn, left to grow throughout winter and end their life around the end of the rainy season (Fig. 8.3, oLIVE-CLIMA; LIFE 11/ENV/000942). They usually are ploughed into soil or left as a mulch to decay on the soil surface (Varela et al. 2014).

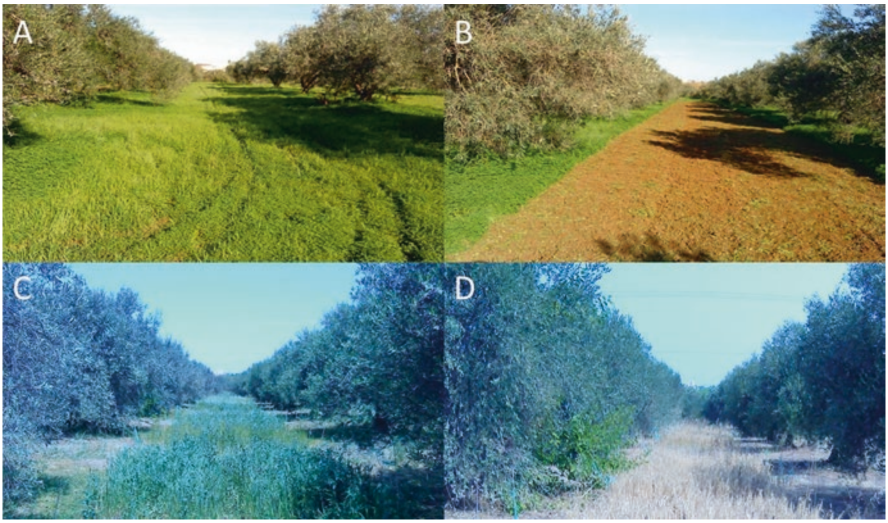

Fig. 8.3 Cover crops in olive orchard: in Mediterranean conditions, cover crops are established during autumn, left to grow throughout winter and end their life around the end of the rainy season either through ploughing into the soil or left as a mulch to decay on the soil surface

Many studies documented the changes in soil properties when the soil management shifts from conventional tillage to cover crop; mainly a reduction of soil erosion (Gómez et al. 2009b), improvement of water storage and physical properties (Palese et al. 2014), and an increase of SOC and nitrogen (Jarecki and Lal 2005). The usage of cover crops and the elimination of tillage practices can significantly improve soil quality in Mediterranean olive groves. Cover crops and non-tillage practices contribute to the atmospheric C sequestration in Mediterranean olive groves (Nieto et al. 2010). Nieto et al. (2012) reported that cover crops were the soil management system that showed the best soil properties in comparison with conventional tillage or no-tillage bare soil. The usage of cover crops and the elimination of tillage practices significantly improve soil quality by increasing the carbon content and SOC stratification. The concentrations of elements such as N and K also increased. The increase in K concentration was related to the input of organic residues (Gómez et al. 2009b) and to the reduction of losses by erosion (Rodríguez-Lizana et al. 2008). However, its effect on olive tree yield is questionable. Many authors reported negative effects on fruit yield (Gucci et al. 2012; Caruso et al. 2011) while other authors (Corleto and Cazzato 2008; Ferraj et al. 2011) did not find a significant effect on olive yield. Sastre et al. (2016) supported the adoption of cover crops in the drought-tolerant olive cultivars in Central Spain. Cover crops have not reduced fruit or oil yield either in heavy or in low yield years.

Weed control through mulching or herbicide use, as alternative practices of tillage, constitute an essential prerequisite for the restriction of soil nutrient and water losses during the tree growth period (Metzidakis et al. 2012). The authors proposed naturaly occurring drought sensitive species such as *Oxalis pes caprae* as cover crops, found in extensive regions of Crete. This weed prevents soil erosion during winter while it dies in spring so it does not compete with the olive for water and nutrients at the periods of drought. In addition, the restriction of tillage to once every 2–3 years for the control of perennial weeds significantly reduced land degradation (Metzidakis et al. 2005). Therefore, the adoption of an integrated soil management system would be a viable and sustainable solution for olive groves in Mediterranean basin.

8.5 Tillage Practices

Soil cultivation by intensive tillage has been traditional over the last two millennia and even before the Roman Empire. In olive groves weed control is mainly implemented through either mechanical tillage or herbicide use (Metzidakis et al. 2012). Modern mechanization has allowed farmers to plough even in steep slopes. Tillage vertically to the contour lines is a widely applied practice in Greek olive groves, resulting to an intense down slope movement of soil (Gerontidis et al. 2001). This is a fact with great interest in the case of soils in Greece that are poor in organic matter. In addition, approximately 50% of olive groves in Spain are tilled to avoid weed competition for water and nutrients, in order to increase olive tree yield (Sastre et al. 2016). This practice causes to a great extent bare soil that is prone to erosion processes, constituting one of the most important land degradation driving processes in the Mediterranean region (Panagos et al. 2014). Tillage favors the oxidation of SOM and has negative effects on soil physical and chemical properties (Rasmussen and Collins 1991) and on soil depth (Arshad and Coen 1992). Superficial soil losses are evident in hilly areas around the Mediterranean and are related to the practice of leaving the soil bare through intensive tillage (Fig. 8.4, oLIVE-CLIMA; LIFE 11/ENV/000942) or herbicides (Fig. 8.5, oLIVE-CLIMA; LIFE 11/ENV/000942). Biodiversity is also heavily affected by improper management practices while very often one or very few plant species are present in the olive tree ground floor (Fig. 8.6, oLIVE-CLIMA; LIFE 11/ENV/000942).

A reduction to intensive tillage in the Mediterranean areas begun in the 1960s mainly driven by the necessity for a reduction in various inputs (fuel, machinery and labor). Chiseling and minimum tillage with small hoe cultivators are now more common than 50 years ago, having even become the traditional system in some areas, substituting the conventional mould board ploughing. The main cropping systems where conservation tillage practices (reduced tillage or no-tillage) are used are field crops with winter cereals in rotations with legumes, sunflower and canola.

The use of no-tillage (NT) and cover crops between rows in perennial crops (olives, nuts and grapes) is increasing in some areas. NT allows agricultural practices that leave the soil undisturbed. NT is the strict form of conservation tillage in which no soil manipulation is done, a direct drilling planter is used for the seeding of annual crops and weeds are chemically controlled. The only soil disturbance is related to the movement of the agricultural machines used for seeding and harvest**.** NT cause various benefits to the soil, such as positive effects on organic matter content and cation exchange capacity (CEC) (Wu et al. 2015), protection of organic matter from high temperature and thus reduction of mineralization (Alvarez et al. 2014), increase to the fraction and stability of macro-aggregates and improvement of water infiltration (Franzluebbers 2002) and soil aeration (Batey 2009). Also, Paustian et al. (2000) showed that the residence time of SOM showed a two-fold

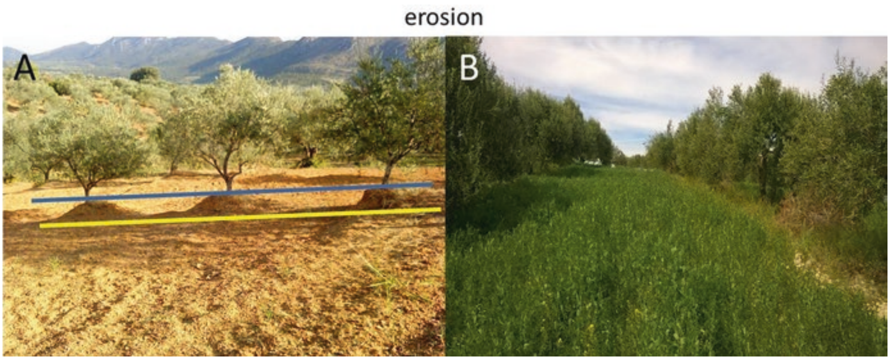

Fig. 8.4 Tillage induced soil erosion: superficial soil losses are evident in hilly areas around the Mediterranean and are related to the practice of leaving the soil bare through intensive tillage (**a**). In contrast, covered soil is protected from erosion (**b**)

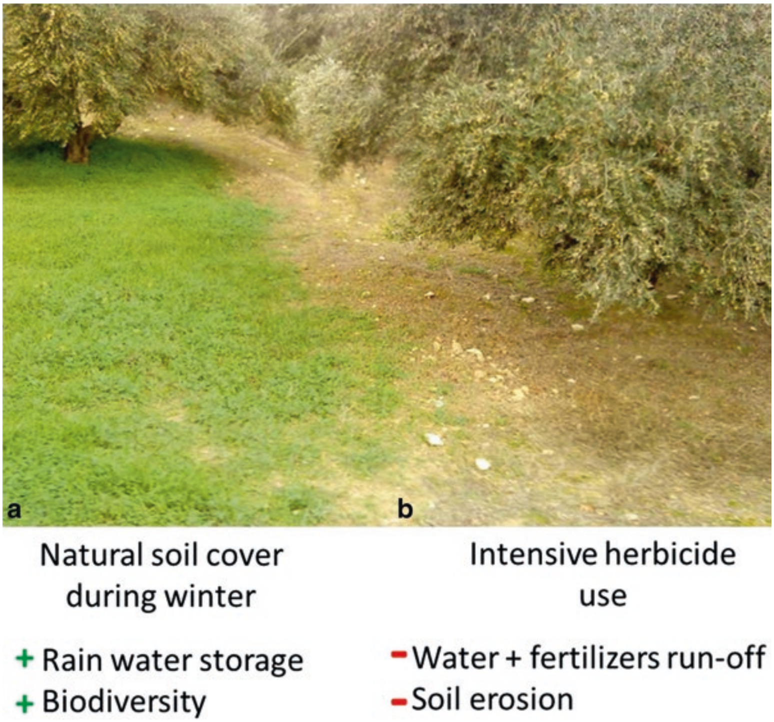

Fig. 8.5 Covered versus bare soil during winter: comparison of neibhouring olive orchards with (**a**) weed soil cover during winter and (**b**) bare soil through intensive herbicides application

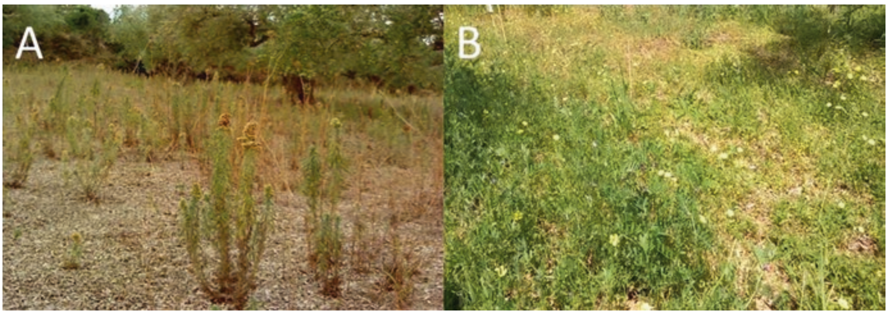

Fig. 8.6 Impact of weed management on biodiversity: biodiversity is also heavily affected by improper management practices while very often one or very few plant species are present in the olive tree ground floor (**a**). In contrast, good orchard management aims at multispecies soil cover (**b**)

increase under no-tillage compared to intensive tillage. Further positive effects are the reduction of soil erosion (De Freitas and Landers 2014), the improvement of soil moisture and the reduction of bulk density (Jin et al. 2011) in the topsoil.

However the development and adoption of NT has been very irregular in the Mediterranean region (Arrue et al. 2007). In southern Europe and Spain, Arrue et al. (2007) reported 10–15% yield improvement under no-tillage, especially in dry years. In west Crete, Greece, Metzidakis et al. (2012) studied the effect of tillage and no tillage, on physical and chemical properties of autochthonous soils that were formed in slopes higher than 10%. Soil organic matter content was higher in the case of no tillage in soils. No statistically significant differences were recorded between the treatments in exchangeable K, pH, equivalent $CaCO_3$ and CEC. Koubouris et al. (2017) concluded that recycling pruning residue and composted olive mill waste without tillage may lead to significant short term positive effects on soil properties compared to an orchard management system where the soil is maintained free of weeds and no organic materials are added, especially in soils with low clay content. However, in wetter, heavier soils in texture, NT can hamper crop emergence and soil workability (Smith et al. 2008), so is not suitable for all soils and bioclimatic regions (Merante et al. 2017).

Reduced tillage (RT) practices are encouraging the reduction of soil disturbance before, during or after crop growing season due to low depth of tillage and to reduced frequency of passes over the soil or to specific tilling; e.g. strip and ridge tillage (Merante et al. 2017). RT practices favor soil aggregation and SOC stabilization (Sheehy et al. 2015; Kabiri et al. 2015).

The ecosystem of the olive is quite stable when compared with other agricultural ecosystems. Cirio (1997) stated that olive grove shows little imbalance, since the number of cultivation practices applied is still very low. The abandonment of olive groves is a phenomenon of great importance because of the trend to return, after a long time, to a “climax” phase where soil and vegetation components are in equilibrium (Loumou and Giourga 2003). Palese et al. (2013) assessed the effect of the long-term land abandonment (minimum tillage and no fertilization) on soil properties. The authors found that SOM, total nitrogen, and pH were significantly higher in the abandoned olive grove. This was attributed to the absence of tillage and the high C/N ratio of natural additions of organic matter. During the transition from a cultivated condition to a climax phase, soil properties may change progressively. Zornoza et al. (2009) concluded that the abandonment of almond orchards for 10–15 years improved soil microbial activity and biomass due to the increment in the vegetation cover, and higher inputs as litter and root exudates. Nevertheless, values of the above parameters are still low compared to forest soils, reflecting that it is not long enough to achieve a significant recovery in soil properties under semi-arid Mediterranean conditions.

On the other hand, the abandonment of olive groves can also lead to erosion in very dry areas of Mediterranean countries (south-east Spain), especially when terraces collapse (Pienkowski and Beaufoy 2002). In fact, no-tillage systems which involve an excessively intensive use of herbicides can expose the soil to severe erosion. The maintenance of a crop cover on 30–50% of the soil area, between tree rows, has proved to be more effective in controlling erosion than bare soil systems based on intensive use of herbicides. In the case of an abandoned olive grove turned into a pastureland, although the land shows an increased production of biomass, its exploitation is intense, having as a consequence the degradation of its soil. This is due to the increased intensity of the erosive phenomena, while at the same time the natural regeneration of vegetation is impeded. Indeed, the soil depth was reduced from 30 to 10 cm and 6 cm after 20 and 30 years of abandonment respectively (Margaris et al. 1988). Palese et al. (2013) noted that the management of extensive cultivation might not induce a disturbance to microbial communities. The soil of the abandoned olive orchard showed a lower number of total bacteria and fungi and a lower microbial diversity, as a result of a sort of specialization trend towards low quality organic substrates.

Reduced tillage and the addition of organic residues improve soil properties and diminish atmospheric CO_2 concentrations by storing carbon in the form of organic matter (IPCC 2000; Jarecki and Lal 2003). Alliaume et al. (2014) note that, when combined with mulching and manure, RT can favor moisture conservation, further reducing runoff and soil erosion because of the greater quantity of water intercepted and stored. In addition, RT or no tillage when combined with reduced use of chemical fertilizers or olive residues, caused reduction of soil erosion and improvement of soil quality (Montes-Borrego et al. 2013; Fernández-Romero et al. 2016).

It is worth noting that sustainable soil management can be achieved with conventional tillage practices when combined with the alternative techniques to apply one of the typical organic wastes of olive groves named *alperujo*, a solid by-product of the two-phase centrifugation method for olive oil extraction, thus tackling the environmental problems such as reducing of soil erosion and waste disposal. The addition of manure alleviated the negative effect of tillage in the soil properties (Mando et al. 2005). Land degradation is prevented by allowing spontaneous annual vegetation to cover the ground as it contributes to the drastic reduction in soil losses (Kosmas et al. 1997). Fernández-Romero et al. (2016) determined SOC in olive groves under different land management systems: Conventional tillage, olive mill waste residues (*alperujo* and/or leaves), no tillage with chipped pruned branches and/or weed control. The authors concluded that the application of oil mill waste olive leaves under conventional tillage (L) was a good management practice to improve SOC and reduce waste. In fact total SOC under management system (L) was significantly higher at 250. Mg ha^{-1} compared to the rest of the other land management practices (101.9–111.3 Mg ha^{-1}). It should be noted that the aforementioned management practices appeared to affect the top 100 cm, as SOC was similar below 100 cm in all the studied soils.

8.6 Irrigation Conditions and Soil Management Practices

Olive orchards are traditionally managed as rain-fed crops. However, in the last years, water demand for olive orchards has been increased in the Mediterranean basin. Although many authors have shown beneficial effects of sustainable practices providing organic amendments on soil properties (Moreno et al. 2009; Montanaro et al. 2012; Koubouris et al. 2017; Kavvadias et al. 2018a), their implementation in olive groves under different irrigation regimes have not yet been systematically tested. A LIFE+ project was initiated (oLIVE-CLIMA; LIFE 11/ENV/000942) aiming to investigate the introduction of new cultivation practices for irrigated and rain-fed olive groves in order to find a cost-effective means of mitigating and adapting to climate change. Cultivation practices were: (a) Introduction of no soil tillage/reduced tillage. (b) Organic matter removed during olive production to be returned and spread on the soil either raw or composted. (c) Enrichment of indigenous weed flora by sowing a mix of selected seeds. (d) Adaptation of tree pruning to maximize the capture of CO_2 through photosynthesis. The project focused specifically on olive-producing areas in Greece, investigating the potential of these areas to increase carbon sequestration by soils, and to reduce greenhouse gases emissions. Project results are available in the project website (http://www.oliveclima.eu/en/).

Under the frame of oLIVE-CLIMA project, the results from a case study regarding long term effects of residue management and cover crops on soil properties in rain-fed and irrigated olive groves located in the south west Peloponnesus, Greece, were reported by Kavvadias et al. (2018b). The effect of addition of organic materials (shredded pruning residues, composted olive mill by-products, green manure) on soil chemical and microbial properties in irrigated and rain-fed olive groves seemed to be affected by climatic conditions and especially by precipitation height. The overall effect of irrigation conditions (irrigated soil parcels to rain-fed soil parcels) was not significant for most of the soil chemical and microbial parameters, due to the fact that the area under study receives relatively large amounts of rainfall (mean annual rainfall 1100 mm) compared to an average of 653 mm over the entirety of Greece and this masked any irrigation effect on soil properties. On the other hand, a similar work (Kavvadias et al. 2018c) took place in the island of Crete, region of Peza, South Greece (mean annual precipitation 460 mm), however soil properties differed between rain-fed and irrigated olive groves. In fact, SOM, total nitrogen, soil basal respiration and soil microbial biomass C significantly increased with irrigation compared to rain-fed conditions, therefore promoting soil fertility. This was attributed to increased soil moisture conditions, which enhance vegetation biomass and the development and activity of microorganisms. Furthermore, the Humic acid/Fulvic acid ratio was significantly higher in irrigated soils compared to rain-fed ones, indicating a better microbial turnover efficiency in irrigated parcels (Piotrowska et al. 2011). In a relevant work, Kourgialas et al. (2016) concluded that irrigation frequency and load should be optimized based on monitoring of precipitation and water storage in soil within the tree's root zone. Moreover, with regards to the aforementioned work (Kavvadias et al. 2018c) the effect of organic matter inputs was dependent on irrigation conditions. It was found that organic matter input practices significantly increased SOM and TN in irrigated fields, while TN was decreased in rain-fed fields and no effect was recorded for SOM. Improving irrigation efficiency through optimizing soil management practices will help to improve soil moisture conservation and favor soil fertility.

8.7 Conclusion

This chapter highlights the current trends in the utilization of soil management techniques in olive groves in the Mediterranean Basin. Olives can maintain the productive possibility in the low fertile and degraded dry Mediterranean soils which are characterized by very high erosion levels. A fact that is becoming more important is when considering that the olive grove exploits marginal productivity in inclining soils that run the increased danger of deterioration. There is a substantial diversity regarding olive orchard management among the Mediterranean countries. In most Mediterranean countries olive trees are a major source of agricultural residues. The sustainable management of olive pruning residues and that of olive mill wastes are very efficient in terms of improving soil quality and protecting from land degradation. In addition, sustainable soil management can be achieved when alternative techniques such as drought tolerant cover crops, appropriate methods of utilization of olive mill waste residues and chipped pruned branches etc. are combined with reduced tillage or no-tillage practices or even with conventional tillage practices. Application of suitable management of olive groves can create a sink increasing the biomass pool. In addition, the dedicated supply of organic matter – partly organic waste – to olive grove soils can promote the ability of soil to serve as sink of carbon, increasing soil carbon. Optimizing carbon balance in olive groves can contribute to climate change mitigation. Increasing C stocks would be beneficial not only for the national GHG accounting procedures, but also for the olive grower income because of the improved productivity (due to agronomic benefits related to increased soil C content) and in turn improved profitability of the overall olive industry. Further research with regards the assessment of the long-term effects of soil management practices have to be carried out in order to restrict the knowledge gaps. Therefore, it is of vital importance the adoption of an integrated soil management system which can effectively improve soil quality in Mediterranean olive groves and protect soil from further degradation. It is urgent to adapt to a design and adjust the local soil management practices, in order to promote soil conservation and increase soil fertility, while controlling the environmental impact. Further research needs:

- Influence of cover crops on soil carbon and nitrogen dynamics and its influence on water and nutrients uptake in Mediterranean semiarid olive groves. Investigation of drought tolerant cover crops in rain-fed olive orchards which could be efficiently controlled in the spring, promoting soil protection without excessive competition for water and nutrients with the olive trees.
- Influence of tillage practices with various types of olive residues on carbon sequestration, nitrogen availability and soil quality across various Mediterranean climate and soil conditions.

In addition, there is a great interest in modeling the changes of soil C pool as good practice for the optimization of frameworks for national measuring and accounting of GHG. A holistic relationship for the Mediterranean olive grove among sustainable soil management practices and soil carbon stocks have to be determined.

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References

Abiven S, Menassero S, Chenu C (2009) The effect of organic inputs over time on soil aggregate stability – a literature analysis. Soil Biol Biochem 41:1–12

Alliaume F, Rossing WAH, Tittonell P, Jorge G, Dogliotti S (2014) Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. Agric Ecosyst Environ 183:127–137

Alvarez C, Alvarez CR, Costantini A, Basanta M (2014) Carbon and nitrogen sequestration in soils under different management in the semi-arid Pampa (Argentina). Soil Till Res 142:25–31

Arampatzis G, Hatzigiannakis E, Pisinaras V, Kourgialas N, Psarras G, Kinigopoulou V, Panagopoulos A, Koubouris G (2018) Soil water content and olive tree yield responses to soil management, irrigation, and precipitation in a hilly Mediterranean area. J Water Clim Change 9(4):672–678

Arrue JL, Cantero-Martlnez C, Cardarelli A, et al (2007) Comprehensive inventory and assessment of existing knowledge on sustainable agriculture in the Mediterranean platform of KASSA (pp 27). KASSA project (Knowledge assessment and sharing on sustainable agriculture) a European Commission-funded project (DG-Research – Contract no. GOCE-CT-2004-505582)

Arshad MA, Coen GM (1992) Characterization of soil quality: physical and chemical criteria. Am J Altern Agric 7:25–31

Balesdent J, Chenu C, Balabane M (2000) Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res 53:215–230

Batey T (2009) Soil compaction and soil management—a review. Soil Use Manag 25:335–345

Bechara E, Papafilippaki A, Doupis G, Sofo A, Koubouris G (2018) Nutrient dynamics, soil properties and microbiological aspects in an irrigated olive orchard managed with five different management systems involving soil tillage, cover crops and compost. J Water Clim Change. https://doi.org/10.2166/wcc.2018.082

Ben Ahmed C, Rouina Ben B, Boukhris M (2009) Chapter 10: Olive tree growth in Tunisia: types, limitations and influences. In: Grossberg SP (ed) Forest management. Nova Science Publishers, Hauppauge

Ben-Gal A (2011) Salinity and olive: from physiological responses to orchard management. Isr J Plant Sci 59:15–28

Benitez E, Nogales R, Campos M, Ruano F (2006) Biochemical variability of olive-orchard soils under different management systems. Appl Soil Ecol 32:221–231

Bonanomi G, Antignani V, Capodilupo M, Scala F (2010) Identifying the characteristics of organic soil amendments that suppress soilborne plant diseases. Soil Biol Biochem 42:136–144

Borrero C, Trillas MI, Ordovás J, Tello JC, Avilés M (2004) Predictive factors for the suppression of Fusarium wilt of tomato in plant growth media. Phytopathology 94:1094–1101

Brevik EC (2012) Soils and climate change: gas fluxes and soil processes. Soil Horiz 53:12–23

Calatrava J, Franco JA (2011) Using pruning residues as mulch: analysis of its adoption and process of diffusion in Southern Spain olive orchards. J Environ Manag 92:620–629

Caruso G, Gucci R, Sifola M (2011) Soil management affects yield components of young olive trees under deficit irrigation. Acta Hortic 924:219–224

Casacchia T, Sofo A, Zelasco S, Perri E, Toscano P (2012) In situ olive mill residual co-composting for soil organic fertility restoration and by-product sustainable reuse. Ital J Agron 7:35–38

Castro J, Fernandez-Ondoρo E, Rodriguez C, Lallena AM, Sierra M, Aguilar J (2008) Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaιn (Spain). Soil Tillage Res 98:56–67

CEC (1992) CORINE soil erosion risk and important land resources – in the southern regions of the European Community EUR 13233. Office for the Official Publications of the European Community, Luxembourg
Cerdà A, Lavee H, Romero-Díaz A, Hooke J, Montanarella L (2010) Soil erosion and degradation on Mediterranean type ecosystems. Land Degrad Dev 21:71–74
Cirio U (1997) Agrochemicals and environmental impact in olive farming. Olivae 65:32–39
Corleto A, Cazzato E (2008) Effects of different soil management practices on production, quality and soil physico-chemical characteristics of an olive grove in Southern Italy. Acta Hortic 767:319–328
Dabney SM, Delgado JA, Meisinger JJ, Schomberg HH, Liebig MA, Kaspar T, Mitchell J, Reeves W (2010) Using cover crops and cropping systems for nitrogen management. In: Delgado JA, Follett RF (eds) Advances in nitrogen management for water quality. SWCS, Ankeny, pp 231–282
De Freitas PL, Landers JN (2014) The transformation of agriculture in Brazil through development and adoption of zero tillage conservation agriculture. Int Soil Water Conserv Res 1:35–46
De Graaff J, Eppink LAAJ (1999) Olive oil production and soil conservation in southern Spain in relation to EU subsidy policies. Land Use Policy 16:259–267
Dexter AR, Richard G, Arrouays D, Czyz EA, Jolivet C, Duval O (2008) Complexed organic matter controls soil physical properties. Geoderma 144:620–627
Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev 30:401–422
Donn S, Wheatley RE, McKenzie BM, Loades KW, Hallett PD (2014) Improved soil fertility from compost amendment increases root growth and reinforcement of surface soil on slope. Ecol Eng 71:458–465
European Commission (2015) Closing the loop – an EU action plan for the circular economy, Brussels, 2 December 2015 COM(2015) 614 final. http://ec.europa.eu/environment/circular-economy/index_en.htm
Farzi R, Gholami M, Baninasab B, Gheysari M (2017) Evaluation of different mulch materials for reducing soil surface evaporation in semi-arid region. Soil Use Manage 33:120–128
Fernández-Escobar R, García-Novelo JM, Molina-Spria C, Parra MA (2012) An approach to nitrogen balance in olive orchards. Sci Hortic 135:219–226
Fernández-Romero ML, Lozano-García B, Parras-Alcántara L, Collins CD, Clark JM (2016) Effects of land management on different forms of soil carbon in olive groves in Mediterranean areas. Land Degrad Dev 27:1186–1195
Ferraj B, Teqja Z, Susaj L et al (2011) Effects of different soil management practices on production and quality of olive groves in southern Albania. J Food Agric Environ 9:430–433
Ferrara G, Mazzeo A, Matarrese AMS, Pacifico A, Fracchiolla IM, Al Chamill Z, Lasorella IC, Montemurro P, Mondelli D (2015) Soil management systems: effects on soil properties and weed flora. S Afr J Enol Vitic 36:11–20
Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res 66:197–205
Freibauer A, Rounsevell MDA, Smith P, Verhagen J (2004) Carbon sequestration in the agricultural soils of Europe. Geoderma 122:1–23
Fresco LO (1996) Agriculture in the lower Guadalhorce Valley. Sustainable land use. Practical guide for the Alora Region, Spain. Agricultural University, Wageningen
Gerontidis St DV, Kosmas C, Detsis B, Marathianou M, Zafirious T, Tsara M (2001) The effect of moldboard plow on tillage erosion along a hillslope. J Soil Water Conserv 56:147–152
Gómez JA, Sobrinho TA, Giráldez JV, Fereres E (2009a) Soil-management effects on runoff, erosion and soil properties in an olive grove of southern Spain. Soil Tillage Res 102:5–13
Gómez JA, Guzmán MG, Giráldez JV, Fereres E (2009b) The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil Tillage Res 106:137–144
Gómez-Muñoz B, Valero-Valenzuela JD, Hinojosa MB, García-Ruiz R (2016) Management of tree pruning residues to improve soil organic carbon in olive groves. Eur J Soil Biol 74:104–113

Goss MJ, Tubeileh A, Goorahoo D (2013) A review of the use of organic amendments and the risk to human health. Adv Agron 120:275–379

Gruhn P, Goletti F, Yudelman M (2000) Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges. Food, agriculture, and the environment, Discussion Paper 32. International Food Policy Research Institute, Washington DC, pp 15–18

Gucci R, Caruso G, Bertolla C et al (2012) Changes of soil properties and tree performance induced by soil management in a high-density olive orchard. Eur J Agron 41:18–27

He SL, Niu QG, Li YY, Nie YL, Hou MF (2015) Factors associated with the diversification of the microbial communities within different natural and artificial saline environments. Ecol Eng 83:476–484

Hernández AJ, Lacasta C, Pastor J (2005) Effects of different management practices on soil conservation and soil water in a rainfed olive orchard. Agric Water Manag 77:232–248

International Olive Oil Council (IOOC) (2007) Production techniques in olive growing, 1st edn. IOOC, Madrid, May 2007

IPCC (2000) Special report on land use, land-use change and forestry. Cambridge University Press, Cambridge

Jarecki MK, Lal R (2003) Crop management for soil carbon sequestration. Crit Rev Plant Sci 22:471–502

Jarecki MK, Lal R (2005) Soil organic carbon sequestration rates in two long-term no-till experiments in Ohio. Soil Sci 170:280–291

Jin H, Hongwen L, Rasaily Rabi G, Qingjie W, Guohua C, Yanbo S, Xiaodong Q, Lijin L (2011) Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system on North China Plain. Soil Tillage Res 113:48–54

Jokela WE, Grabber JH, Karlen DL, Balser TC, Palmquist DE (2009) Cover crop and liquid manure effects on soil quality indicators in a corn silage system. Agron J 101:727–737

Kabiri V, Raiesi F, Ghazavi MA (2015) Six years of different tillage systems affected aggregate-associated SOM in a semi-arid loam soil from Central Iran. Soil Tillage Res 154:114–125

Kavvadias V, Papadopoulou M, Vavoulidou E et al (2018a) Chapter 10 – Effects of carbon inputs on chemical and microbial properties of soil in irrigated and rainfed olive groves. In: Muñoz MÁ, Zornoza R (eds) Soil Management and Climate Change. Academic, London, pp 137–150

Kavvadias V, Papadopoulou M, Vavoulidou E et al (2018b) Effect of addition of organic materials and irrigation practices on soil quality in olive groves. J Water Clim Change 9(4):775–785

Kavvadias V, Papadopoulou M, Vavoulidou E et al (2018c) Effect of sustainable management of olive tree residues on soil fertility in irrigated and rain-fed olive orchards. J Water Clim Change 9(4):764–774

Kosmas C, Danalatos NG, Cammeraat LH et al (1997) The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena 29:45–59

Koubouris GC, Kourgialas NN, Kavvadias V, Digalaki N, Psarras G (2017) Sustainable agricultural practices for improving soil carbon and nitrogen content in relation to water availability – an adapted approach to Mediterranean olive groves. Commun Soil Sci Plant Anal 48:2687–2700

Kourgialas NN, Doupis G, Papafilippaki A, Psarras G, Koubouris G (2016) Seasonal variation of soil moisture in irrigated olive trees. Procedia Eng 162:471–475

Kourgialas NN, Doupis G, Psarras G, Sergentani C, Digalaki N, Koubouris G (2017) Soil management and compost effects on salinity and seasonal water storage in a Mediterranean drought-affected olive tree area. Desalin Water Treat:1–7

Kushwaha CP, Tripathi SK, Singh K (2000) Variations in soil microbial biomass and N availability due to residue and tillage management in a dryland rice agroecosystem. Soil Tillage Res 56:153–166

Loumou A, Giourga C (2003) Olive groves: "the life and identity of the Mediterranean". Agric Hum Values 20:87–95

Lozano-García B, Parras-Alcántara L, del Toro M (2011) The effects of agricultural management with oil mill by-products on surface soil properties, runoff and soil losses in southern Spain. Catena 85:187–193

Mando A, Ouattara B, Sédogo M, Stroosnijder L, Ouattara K, Brussaard L, Vanlauwe B (2005) Long-term effect of tillage and manure application on soil organic fractions and crop performance under Sudano-sahelian conditions. Soil Tillage Res 80:95–101
Manios T (2004) The composting potential of different organic solid wastes: experience from the island of Crete. Environ Intern 29:1079–1089
Margaris NS, Mardiris Th, Chairopoulos G (1988) The 'retreat' of olive groves-forest. Proceedings of scientific meeting, the Aegean olive groves, February 25–27, pp 18–25. Mytilini, Greece: Edition Elaiourgiki [in Greek]
Markakis E, Koubouris G, Kavroulakis G, Psarras G, Sergentani, C, Kalaitzaki A (2017) Pruning residue management associated pathogens in olive. Working Group "Integrated protection of olive crops". In: Perdikis D, Stathas G, Papadopoulos N, Lucchi A (eds) Proceedings of the 7th meeting at Kalamata (Greece), 11–14 May, 2015. ISBN 978-92-9067-305-7 [XXIV + 166 pp] IOBC-WPRS Bulletin vol 121, 161–165
Martínez-Mena M, López J, Almagro M, Boix-Fayos C, Albaladejo J (2008) Effect of water erosion and cultivation on the soil carbon stock in a semiarid area of South-East Spain. Soil Tillage Res 99:119–129
Merante P, Dibari C, Ferrise R et al (2017) Adopting soil organic carbon management practices in soils of varying quality: implications and perspectives in Europe. Soil Tillage Res 165:95–106
Metzidakis I, Kosmas C, Moustakas N, Koubouris G, Kassidonis E (2005) Effect of different cultural systems on the environment in marginal olive orchards: case study in Crete (Greece). "International course on the olive tree and environmental protection" International Olive Oil Council (IOOC) Reus, Spain, 23–30 October 2005
Metzidakis I, Martinez-Vilela A, Castro Nieto G, Basso B (2008) Intensive olive orchards on sloping land: good water and pest management are essential. J Environ Manag 89(2):120–128. https://doi.org/10.1016/j.jenvman.2007.04.028
Metzidakis I, Koubouris G, Kassidonis E, Sergendani C, Giannakaki A, Kosmas C, Moustakas N (2012) Impact of soil management practices on physical and chemical properties of soils formed in marls, conglomerates or schists in sloping olive groves. Acta Hortic 949
Montanaro G, Celano G, Dichio B, Xiloyannis C (2010) Effects of soil-protecting agricultural practices on soil organic carbon and productivity in fruit tree orchards. Land Degrad Dev 21:132–138
Montanaro G, Dichio B, Bati CB, Xiloyannis C (2012) Soil management affects carbon dynamics and yield in a Mediterranean peach orchard. Agric Ecosyst Environ 161:46–54
Montes-Borrego M, Navas-Cortés JA, Landa BB (2013) Linking microbial functional diversity of olive rhizosphere soil to management systems in commercial orchards in southern Spain. Agric Ecosyst Environ 181:169–178
Moreno B, Garcia-Rodriguez S, Cañizares R, Castro J, Benítez E (2009) Rainfed olive farming in south-eastern Spain: Long-term effect of soil management on biological indicators of soil quality. Agric Ecosyst Environ 131:333–339
Nieto OM, Castro J, Fernández E, Smith P (2010) Simulation of soil organic carbon stocks in a Mediterranean olive grove under different soil-management systems using the Roth C model. Soil Use Manage 26:118–125
Nieto OM, Castro J, Fernández E (2011) Long-term effects of residue management on soil fertility in Mediterranean olive grove: simulating carbon sequestration with Roth C model. In: Burcu E, Gungor O (eds) Principles, application and assessment in soil science. Intech, Rijeka, pp 130–150
Nieto OM, Castro J, Fernández E (2012) Sustainable agricultural practices for Mediterranean olive groves. The effect of soil management on soil properties. Span J Soil Sci 2:70–77
Ordóñez-Fernández R, Repullo-Ruibérriz de Torres M, Román-Vázquez J, González-Fernández P, Carbonell-Bojollo R (2015) Macronutrients released during the decomposition of pruning residues used as plant cover and their effect on soil fertility. J Agric Sci 153:615–630
Palese AM, Magno R, Casacchia T et al (2013) Chemical, biochemical and microbiological properties of soils from abandoned and extensively cultivated olive orchards. Sci World J 496278

Palese AM, Vignozzi N, Celano G et al (2014) Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Tillage Res 144:96–109

Panagos P, Meusburger K, Ballabio C, Borrelli P, Alewell C (2014) Soil erodibility in Europe: a high-resolution dataset based on LUCAS. Sci Total Environ 479–480:189–200

Park JH, Lamb D, Paneerselvam P, Choppala G, Bolan N, Chung JW (2011) Role of organic amendments on enhanced bioremediation of heavy metal(loid) contaminated soils. J Hazard Mater 185:549–574

Pastor M (2004) Sistemas de manejo de suelo. In: Barranco D, Fernández-Escobar R, Rallo L (eds) El cultivo del olivo. Mundi Prensa, Madrid, pp 231–285

Paustian K, Six J, Elliott ET, Hunt HW (2000) Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48:147–163

Pienkowski M, Beaufoy G (2002) The environmental impact of olive oil production in the European Union: practical options for improving the environmental impact. European Forum on Nature Conservation and Pastoralism

Piotrowska A, Rao MA, Scotti R, Gianfreda L (2011) Changes in soil chemical and biochemical properties following amendment with crude and dephenolized olive mill waste water (OMW). Geoderma 161:8–17

Ramakrishna A, Tam HM, Wani SP, Long TD (2006) Effects of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. Field Crops Res 95:115–125

Ramos ME, Benítez E, García PA, Robles AB (2010) Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: effects on soil quality. Appl Soil Ecol 44:6–14

Rasmussen PE, Collins HP (1991) Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semiarid regions. Adv Agron 45:93–134

Regni L, Nasini L, Ilarioni L, Brunori A, Massaccesi L, Agnelli A, Proietti P (2017) Long term amendment with fresh and composted solid olive mill waste on olive grove affects carbon sequestration by prunings, fruits, and soil. Front Plant Sci 7:2042

Rewald B, Leuschner C, Wiesman Z, Ephrath JE (2011) Influence of salinity on root hydraulic properties of three olive varieties. Plant Biosyst 145:12–22

Rodríguez-Lizana A, Espejo-Pérez AJ, González-Fernández P, Ordóñez-Fernández R (2008) Pruning residues as an alternative to traditional tillage to reduce erosion and pollutant dispersion in olive groves. Water Air Soil Pollut 193:165–173

Rui Y, Murphy DV, Wang X, Hoylea FC (2016) Microbial respiration, but not biomass, responded linearly to increasing light fraction organic matter input: consequences for carbon sequestration. Sci Rep 6:35496

Russo G, Vivaldi GA, De Gennaro B, Camposeo S (2015) Environmental sustainability of different soil management techniques in a high-density olive orchard. J Clean Prod 107:498–508

Sánchez B, Álvaro-Fuentes J, Cunningham R, Iglesias A (2014) Towards mitigation of greenhouse gases by small changes in farming practices: understanding local barriers in Spain. Mitig Adapt Strateg Glob 4:1–34

Sánchez B, Iglesias A, McVittie A, Alvaro-Fuentes J, Ingram J, Mills J, Lesschen JP, Kuikman P (2016) Management of agricultural soils for greenhouse gas mitigation: learning from a case study in NE Spain. J Environ Manag 170:37–981

Sánchez-Monedero MA, Cayuela ML, Mondini C, Serramiá N, Roig A (2008) Potential of olive mill wastes for soil C sequestration. Waste Manag 28:767–773

Sastre B, Ángeles Pérez-Jiménez M, Bienes R., García-Díaz A, and de Lorenzo C (2016) The effect of soil management on olive yield and VOO quality in a rainfed olive grove of Central Spain. J Chem Article ID 4974609, 15pages

Scotti R, Bonanomi G, Scelza R, Zoina A, Rao MA (2015) Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. J Soil Sci Plant Nutr 15(2):333–352

Sheehy J, Regina K, Alakukku L, Six J (2015) Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in northern European agroecosystems. Soil Tillage Res 150:107–113

Smith P, Nabuurs GJ, Janssens IA et al (2008) Sectoral approaches to improve regional carbon budgets. Clim Chang 88:209–249

Sofo A, Nuzzo V, Palese AM, Xiloyannis C, Celano G, Zukowskyj P, Dichio B (2005) Net CO_2 storage in Mediterranean olive and peach orchards. Sci Hortic 107:17–24

Sofo A, Palese AM, Casacchia T, Xiloyannis C (2014) Chapter 20 Sustainable soil management in olive orchards: effects on telluric microorganisms. In: Ahmad P, Rasool S (eds) Emerging technologies and management of crop stress tolerance volume 2: a sustainable approach. Academic, London, pp 471–483

Soria L, Fernández E, Pastor M, Aguilar J, Muñoz JA (2005) Impact of olive-orchard cropping systems on some soil physical and chemicals properties in southern Spain. In: Faz A, Ortiz R, Mermut AR (eds) Advances in geoecology, vol 36. Catena Verlag, Reiskirchen, pp 428–435

Toscano P, Casacchia T, Zaffina F (2009) The “in farm” olive mill residual composting for by-products sustainable reuse in the soils organic fertility restoration. In: Proceedings of the eighteenth symposium of the International Scientific Centre of Fertilizers—more sustainability in agriculture: new fertilizers and fertilization management, Rome, pp 116–121

Varela MF, Scianca CM, Taboada MA, Rubio G (2014) Cover crop effects on soybean residue decomposition and P release in no-tillage systems of Argentina. Soil Tillage Res 143:59–66

Wells AT, Chan KY, Cornish PS (2000) Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. Agric Ecosyst Environ 80:47–60

Widmer F, Rasche F, Hartmann M, Fliessbach A (2006) Community structures and substrate utilization of bacteria in soils from organic and conventional farming systems of the DOK long-term field experiment. Appl Soil Ecol 33:294–307

Wu T, Milner H, Díaz-Pérez JC, Ji P (2015) Effects of soil management practices on soil microbial communities and development of southern blight in vegetable production. Appl Soil Ecol 91:58–67

Xiloyannis C, Montanaro G, Dichio B (2016) Sustainable orchard management in semi-arid areas to improve water use efficiency and soil fertility. Acta Hortic:425–430

Yassoglou N (1971) A study of the soils of Messara Valley in Crete. Greece Nuclear Research Centre, Athens

Zomer R, Bossio AD, Sommer R, Verchot L (2017) Global sequestration potential of increased organic carbon in cropland soils. Sci Rep 7. https://doi.org/10.1038/s41598-017-15794-8

Zornoza R, Mataix-Solera J, Guerrero C, Arcenegui V, Mataix-Beneyto J (2009) Comparison of soil physical, chemical, and biochemical properties among native forest, maintained and abandoned almond orchards in mountainous areas of eastern Spain. Arid Land Res Manage 23:267–282

9 Microbiome of Rhizospheric Soil and Vermicompost and Their Applications in Soil Fertility, Pest and Pathogen Management for Sustainable Agriculture

Jayakumar Pathma, Gurusamy Raman, and Natarajan Sakthivel

Abstract

Plant rhizospheric soil is rich in microbes due to the release of exudates that serve as food for microbes. Metabolic activity of the root system and the nature of soil influence the microbial population. Through the process of mineralization, microbes assimilate the nitrogen and other essential nutrients. Specific strains of bacteria that inhabit the rhizospheric region are specifically termed as "plant growth promoting rhizobacteria" and therefore, used as "biofertilizers" to manage soil fertility. This group of bacteria is also termed as "biocontrol agents" due to their potential to suppress pests and pathogens that attack crop plants. In the agriculture field soil, earthworms also play a key role in nutrient cycling through their interaction with soil microbes. Therefore, earthworm cast microbiome receives greater attention. In this chapter, we propose to describe the biological role of rhizospheric soil and vermicompost bacteria and their mechanisms that mediate soil fertility, plant growth promotion and biocontrol of pests and pathogens.

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Rhizospheric soil · Mineralization · Biofertilizers · Soil fertility · Microbiome · Vermicompost · Biocontrol

9.1 Introduction

The soil is a huge reserve of diverse microbial communities and plant rhizosphere though only a narrow zone is an active interface of plant-microbial interaction. It is estimated that per gram of root contains approximately 10^{11} microbial cells and includes more than 30,000 species of prokaryotes (Berendsen et al. 2012). Rhizospheric microbiomes greatly influence plant growth, development and immunity by participating in nutrient and energy transfer as well as chemical signalling mechanisms. In turn, the diversity of rhizospheric microbiome is influenced by plant genotype, developmental stage, root exudates and soil physical and chemical properties (Kawasaki et al. 2016; Qiao et al. 2017). The rhizobacteria are broadly classified as plant growth-promoting rhizobacteria (PGPR) and plant deleterious rhizobacteria (PDB) based on their beneficial and deleterious effects on plant growth (Kloepper et al. 1980). Mechanisms through which PGPR strains enhance seed germination and plant growth include their ability to recycle nutrients, solubilize minerals, synthesize vitamins, amino acids, antagonistic metabolites, plant growth promoting hormones and enzymes and induction of resistance in host plants. Indirectly beneficial microbes promote plant growth by preserving the plant health by competing with phytopathogens for food thereby, suppressing them in addition to antibiotic production (Compant et al. 2010; Figueiredo et al. 2010). PGPR includes bacteria belonging to genera *Acinetobacter*, *Alcaligenes*, *Arthrobacter*, *Azospirillum*, *Bacillus*, *Bradyrhizobium*, *Burkholderia*, *Enterobacter*, *Flavobacterium*, *Pseudomonas* and *Rhizobium* (Saharan and Nehra 2011; Ahemad and Kibret 2014). Indiscriminate use of agrochemicals has polluted the ecosystem and dilapidated soil-dwelling micro and macro fauna. Hence, supplementing the soil with composts rich in antagonistic microbes has become mandatory. Compared to traditional thermophilic composts, applications of mesophilic vermicompost is gaining popularity due to its rich microbial diversity with biofertilizing and biocontrol ability. Suhane (2007) documented that the total bacterial count was more than 10^{10} per gram of vermicompost and it included *Azotobacter, Nitrobacter*, *Rhizobium*, phosphate solubilizing bacteria, and actinomycetes ranging from 10^2–10^6/g of vermicompost. Natural soil macrofauna especially earthworms play a significant role in structuring the rhizospheric microbial diversity and processes (Braga et al. 2016). Earthworms, the ecosystem engineers ingest rhizospheric soil along with the organic matter and rhizospheric microbiome. The beneficial rhizosphere bacteria namely *Azotobacter*, *Azosprillium*, *Bacillus*, *Pseudomonas* and *Rhizobium* gets activated or increased due to the ideal micro-environment in the gut of the earthworm. Therefore, earthworm activity increases the population of PGPR and thus, in turn, suppresses the growth of soil-borne phytopathogens (Sinha et al. 2010; Pathma and Sakthivel 2012). Vermicompost microbiome is influenced by the parent material and the earthworm species involved. Vermicomposting, carried out by earthworm gut-associated mesophilic bacteria and fungi produced vermicompost dominated by Actinobacteria and γ-Proteobacteria (Vivas et al. 2009). Vaz-Moreira et al. (2008) reported the occurrence of *Bacillus benzoevorans*, *B. cereus, B. licheniformis*, *B. macrolides*, *B. megaterium*, *B. pumilus*, *B. subtilis*, *Pseudomonas* spp., *P. libaniensi*, *Cellulosimicrobium cellulans*, *Geotrichum* spp., *Kocuria palustris*, *Microbacterium* spp., *M. oxydans*, *Sphingomonas* sp., and *Williopsis californica* in vermicomposts. Investigations on earthworm gut microbes showed the presence of *Aeromonas*, *Azotobacter*, *Bacillus*, *Clostridium*, *Enterobacter*, *Flavobacterium*, *Gordonia*, *Klebsiella*, *Mycobacterium*, *Nocardia*, *Proteus*, *Pseudomonas*, *Serratia* and *Vibrio* with the ability to promote plant growth, fix nitrogen, solubilize phosphorous and act as biocides (Vega and Victoria 2009). Pathma and Sakthivel (2013) reported 193 strains of potent vermicompost bacteria with antagonistic and biofertilizing ability belonging to different genera namely *Acinetobacter*, *Arthrobacter*, *Bacillus*, *Cellulomonas*, *Chryseobacterium*, *Enterobacter*, *Microbacterium*, *Paenibacillus*, *Pseudomonas*, *Pseudoxanthomonas*, *Rheinheimera*, *Rhodococcus* and *Stenotrophomonas* from the compost produced by *Eisenia foetida*.

9.2 Role of Rhizospheric Soil and Vermicompost Bacteria in Soil Fertility

Soil, "the soul of infinite life" is a vibrant habitat of enormous life forms especially microbes, earthworms and soil-dwelling arthropods. Though soil fertility is measured by its nutrient content, it is the soil microbial community especially the rhizospheric microbiome which makes the soil productive. The earthworms and their castings namely the vermicompost also influence the soil microbes especially in soils dilapidated due to intensive cropping and irresponsible human activities. Soil rhizospheric bacteria actively participates in fixation of atmospheric nitrogen, conversion of organic nitrogen into inorganic forms such as NH_4^+ and NO_3^- that could be easily assimilated by plants; solubilisation of insoluble minerals such as phosphorous by secretion of phosphatases and organic acids and also affect the availability of iron, manganese and sulphur to the plants by redox reactions. Thus, rhizobacteria play a pivotal role in geochemical nutrient cycling and availability of macro and micronutrient to the plants and other soil microbes, as well as participate in the biological control of phytopathogens. Due to their active beneficial role in plant growth and health the rhizobacteria were termed as PGPR (Vega 2007). Earthworm activity enhances the population of beneficial soil microbes and vermicomposts are a rich source of beneficial bacteria with fertilizing and biocontrol potential (Pathma and Sakthivel 2012, 2013). Nitrogen tops the phytonutrient chart as an essential macronutrient. Though atmosphere contains 78% of nitrogen they cannot be as such assimilated by plants and have to be converted into plant absorbable form. Rhizosphere contains symbiotic nitrogen-fixing microorganisms such as *Allorhizobium*, *Azorhizobium*, *Bradyrrhizobium*, *Frankia*, *Mesorhizobium*, *Rhizobium* and *Sinorhizobium* associated with legumes (Hayat et al. 2012; Rashid et al. 2015) as well as non-symbiotic N_2 fixing bacteria such as *Acetobacter*, *Achromobacter*, *Alcaligenes*, *Arthrobacter*, *Azomonas*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Beijerinckia*, *Clostridium*, *Corynebacterium*, *Derxia*, *Enterobacter*, *Klebsiella*, *Pseudomonas*, *Rhodospirillum* and *Xanthobacter* (Vessey 2003; Vega 2007; Barriuso et al. 2008). Various anaerobic nitrogen-fixing bacteria such as *Clostridium beijerinckii, C. butyricum* and *C. paraputrificum* were found to inhabit the alimentary canal of *E. foetida* (Citernesi et al. 1977). Gut contents of *Lumbricus rubellus* and *Octolasium lacteum* were found to contain more numbers of culturable denitrifiers (Karsten and Drake 1997). Nearly 52% of vermicompost bacteria tested positive for nitrate reductase activity (Pathma and Sakthivel 2013). Gopal et al. (2009) reported free-living N_2 fixers, *Azospirillum*, *Azotobacter*, autotrophic *Nitrobacter*, *Nitrosomonas* and ammonifying bacteria which promoted plant growth by nitrification from *Eudrilus* sp. vermicompost. Stephens et al. (1994) documented increased root nodulation and nitrogen fixation in legumes by *Rhizobium meliloti* L5-30R isolated from *Aporrectodea trapezoids* and *Microscolex dubious*. The legume-root nodulating, micro symbiotic nitrogen-fixing bacterium *Bradyrhizobium japonicum* from *L. terrestris* showed the improved distribution of nodules on soybean roots (Rouelle 1983) (Table 9.1).

Table 9.1 Diversity of vermicompost bacteria and their functional traits

Vermicompost bacteria	Functional traits	References
Rhizobium japonicum, *Pseudomonas putida*	Plant growth promotion	Madsen and Alexander (1982)
Bradyrhizobium japonicum	Improved distribution of nodules on soybean roots	Rouelle (1983)
P. corrugata 214OR	Suppress *Gaeumannomyces graminis* var. *Tritd* in wheat	Doube et al. (1994)
R. meliloti L5-30R	Increased root nodulation and nitrogen fixation in legumes	Stephens et al. (1994)
Bacillus spp., *B. megaterium*, *B. pumilus*, *B. subtilis*	Antimicrobial against *Enterococcus faecalis* DSM 2570, *Staphylococcus aureus* DSM 1104	Vaz-Moreira et al. (2008)
Fluorescent pseudomonads, filamentous actinomycetes	Suppress *Fusarium oxysporum* f. sp. *asparagi* and *F. proliferatum* in asparagus, *Verticillium dahlia* in eggplant and *F. oxysporum* f. sp. *lycopersici* race 1 in tomato	Elmer (2009)
Nocardioides oleivorans, *Streptomyces griseinus*, *S.olivoviridis*, *S.praecox*, *S. pulveraceus*, *S. microflavus*, *S. globisporus*, *S. baarnensis*, *S. sindenensis*, *S. coelicolor*, *S. violascens*, *S. somaliensis*, *S. felleus*, *Staphylococcus epidermidis*	Chitinase production	Yasir et al. (2009)

(continued)

Table 9.1 (continued)

Vermicompost bacteria	Functional traits	References
Non- symbiotic N_2 fixers, *Azospirillum*, *Azotobacter*, *Nitrobacter*, autotrophic *Nitrosomonas*, Ammonifiers, phosphate solubilizers, *Pseudomonas*, cellulose degraders, silicate solubilizers	Plant growth promotion by nitrification, solibilization of phosphorous, silicate and other minerals, production of cellulase and antagonism	Gopal et al. (2009)
Species of *Pseudomonas*, *Bacillus*, *Acinetobacter*, *Microbacterium*, *Chryseobacterium*, *Arthrobacter*, *Enterobacter*, *Rheinheimera*, *Pseudoxanthomonas*, *Stenotrophomonas*, *Cellulomonas, Rhodococcus*	Production of indole-3-acetic acid, 1-aminocyclopropane-1-carboxylate deaminase, phosphate solubilization, nitrate reduction, antagonistic against *Sarocladium oryzae*, *F. oxysporum*, *Pestalotia theae*, *Macrophomina phaseolina*, *Curvularia lunata*, *Colletotrichum gloeosporioides*, *Cylindrocladium floridanum*, *Cy. scoparium*, *Bipolaris oryzae*, human pathogenic strains of *B. subtilis*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonads* sp., *Vibrio cholerae*, *Candida albicans*	Pathma and Sakthivel (2013)
Bacteroides, *Corynebacterium*, *Mobiloncus*, *Microbacterium*, *Microccocus*, *Peptostreptococcus*, and *Streptomyces*	Cellulose degradation by cellulase production	Torino et al. (2013)
Lactobacillus viridescense, *L. minor*, *Bacillus pumilus*, *B.licheniformis*, *Flavobacterium*	Production of amylase, endoglucanase, cellulase, sucrose, protease	Sumathi and Thaddeus (2013)
Aeromonas hydrophila, *Clostridium viride*, *C. propionicum*, *C. mayombei*, *C. glycolicum*, *Methanoregula* spp., *Methanobacterium formicicum*, *Succinispira mobilis*	Methanogenesis and organic carbon turn over	Schulz et al. (2015)

Solubilization of organic and inorganic phosphorous is an essential trait of plant growth promoting bacteria with regard to plant nutrition and remediation of polluted soils. Rhizospheric bacteria belonging to genera such as *Achromobacter*, *Acinetobacter*, *Aerobacter*, *Agrobacterium*, *Bacillus*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Klebsiella*, *Mesorhizobium*, *Micrococcus*, *Pseudomonas* and *Rhizobium* (Villegas and Fortin 2001); *Pseudomonas aeruginosa*, *P. fluorescens*, *P. fulva*, *P. monteilii*, *P. mosselii*, *P. plecoglossicida* and *P. putida* (Ravindra et al. 2008); *Bacillus* sp., *B. cereus*, *B. megaterium*, *B. thuringiensis*, *Burkholderia* sp., *B. caryophylli*, *Enterobacter intermedium*, *Pseudomonas cichorii* and *Pseudomonas syringae* (Kim et al. 2004; Tao et al. 2008; Oliveira et al. 2009; Delfim et al. 2018), *Pseudomonas* sp. and *P. knackmussii* (Cao et al. 2018) have been reported to solubilize phosphorous. Findings of Pathma and Sakthivel (2013) showed that out of 193 beneficial bacteria isolated from vermicompost, 51 strains belonging to various genera with the majority of them belonging to *Bacillus* and *Pseudomonas* followed by *Acinetobacter*, *Enterobacter* and *Microbacterium* etc., were known to solubilize phosphorous efficiently thereby making them available for assimilation by plants.

9.3 Role of Rhizospheric Soil and Vermicompost Bacteria for Plant Growth Promotion

Beneficial rhizobacteria promote plant growth directly by fixation of atmospheric nitrogen; production of phytohormones such as auxins, gibberellins, cytokinins; enzymes such as 1-aminocyclopropane-1-carboxylate (ACC) deaminase and phosphatase which helps to lower ethylene concentration and solubilization of phosphorous, respectively. Pathma and Sakthivel (2013) reported 193 plant growth promoting vermicompost bacteria of which two bacterial strains such as *Pseudomonas* sp. FPVC5 and *B. subtilis* BVC53 with high temperature and salinity tolerance possessed an array of plant growth-promoting traits such as the production of indole 3-acetic acid (IAA), ACC deaminase, siderophores and broad-spectrum antagonistic properties. Additionally, *Pseudomonas* sp. FPVC5 solubilized phosphate and synthesized hydrogen cyanide (HCN). PGPR strains are known to be prolific producers of phytohormones such as auxins, cytokinin, and gibberellins (Pliego et al. 2011; Saharan and Nehra 2011; Hayat et al. 2012). Several reports evidenced the presence of plant growth regulators such as auxins, gibberellins, cytokinins of microbial origin in appreciable quantities in vermicompost (Krishnamoorthy and Vajranabhiah 1986; Tomati et al. 1988; Pathma and Sakthivel 2012). IAA plays a key role in the regulation of plant growth, development and differentiation (Moore 1989). Zakharova et al. (1999) reported that nearly 80% of rhizosphere bacteria such as *Pseudomonas*, *Bacillus*, *Paenibacillus*, *Bradyrhizobium, Enterobacter, Xanthomonas, Azospirillum, Alcaligenes, Azotobacter, Acetobacter* and *Agrobacterium* produced IAA (Tien et al. 1979; Badenosch-Jones et al. 1982; Srinivasan et al. 1996; Lebuhn et al. 1997; Asghar et al. 2002; Patten and Glick 2002). Nearly 26% of bacteria isolated from goat manure composted using *E. foetida*, belonging to the genera *Pseudomonas*, *Bacillu*s, *Acinetobacter*, *Chryseobacterium*, *Arthrobacter*, *Paenibacillus*, *Enterobacter* and *Stenotrophomonas* produced IAA (Pathma and Sakthivel 2013). IAA producing bacteria help in the development of the plant root system and thereby, enhance nutrient uptake by plants (Patten and Glick 2002). Cytokinins from *Pseudomonas*, *Bacillus, Paenibacillus* and *Arthrobacter* spp. in plant rhizosphere are reported to increase seedling vigour (Garcia de Salamone et al. 2001). Baca and Elmerich (2007) documented cytokinin production by strains of *Pseudomonas fluorescens*, *P. putida, Azotobacter chroococcum* and *A. beijerinckii*. Gibberellins from *Azospirillum brasilense* promote shoot growth, elongation and improve root hair density (Fulchieri et al. 1993). Cassan et al. (2001) reported that gibberellins from *A. brasilense* and *A. lipoferum* bring about the reversion of dwarfism in maize and rice.

Plant growth promoting rhizobacteria namely *P. alcaligenes*, *P. aeruginosa*, *P. fulva*, *P. monteilii*, *P. plecoglossicida* and *P. putida* (Pathma et al. 2010) and *B.*

halotolerans, *B. licheniformis*, *B. pumilus* and *B. subtilis* and members belonging to *Achromobacter*, *Agrobacterium*, *Azospirillum*, *Burkholderia*, *Enterobacter*, *Ralstonia* and *Rhizobium* (Belimov et al. 2001) were reported to produce ACC deaminase. Pathma and Sakthivel (2013) reported that around 64% of bacteria isolated from *E. foetida* vermicompost comprising of genera *Acinetobacter*, *Arthrobacter*, *Bacillus*, *Chryseobacterium* *Enterobacter*, *Paenibacillus*, *Pseudomonas* and *Rhodococcus* produced enzyme ACC deaminase. ACC deaminase enzyme enhances plant growth by nullifying the detrimental effects of ethylene in plants and helps in establishing healthy root system to tolerate biotic and abiotic stresses (Belimov et al. 2001; Pathma et al. 2010).

9.4 Role of Rhizospheric Soil and Vermicompost Bacteria in Disease Management

Rhizospheric bacteria act as the first line of defence against soil-borne phytopathogens by avoiding their primary infection and subsequent spread thereby safeguarding the plant's health. Arancon et al. (2007) documented the presence of beneficial microbes with biocontrol properties against phytopathogens and plant pests in vermicompost.

9.4.1 Bacterial Pathogens

Spraying *B. subtilis* (S-12) reduced the incidence of citrus canker caused by bacterium *Xanthomonas* axonopodis pv. *citri* in acid lime *Citrus aurantifolia* (Das et al. 2014). Krause et al. (2003) reported the suppression of bacterial leaf-spot of radish caused by *Xanthomonas campestris* pv. *armoraciae* by rhizobacterial strain identified as *Bacillus* sp. Bacterial leaf spot of tomato caused by *Xanthomonas campestris* pv. *vesicatoria* was effectively controlled by *Cellulomonas turbata* BT1 and *Pseudomonas syringae* Cit7 (Byrne et al. 2005). Strains of Agrobacterium radiobacter such as K84, 0341 were known to control crown gall disease caused by *Agrobacterium tumefaciens* in stone fruit (Lopez et al. 1989). Ozaktan and Bora (2004) documented that epiphytic bacteria such as *Pantoea agglomerans* strain Eh-24 and strains of fluorescent pseudomonads were effective against fire blight of pear caused by *Erwinia amylovora* as well as blossom blight of pear caused by *Pseudomonas syringae*. Beneficial microbial communities associated with rhizosphere and vermicompost can be used as effective biocontrol agents against phytopathogenic bacteria.

9.4.2 Fungal Pathogens

PGPR strains such as *Pseudomonas fluorescens* and *Serratia marcescens* suppressed anthracnose in cucumber (Liu et al. 1995); *Pseudomonas putida* TRL2-3, *Micrococcus luteus* TRK2-2 and *Flexibacteraceae bacterium* MRL412 controlled late blight in potato (Kim and Jeun 2006). Pseudomonas strain B10 suppressed Fusarium wilt caused by *Fusarium oxysporum* f. sp. *lini.* (Kloepper et al. 1980). *Bacillus* spp. were effective against *Alternaria solani*, *Aspergillus flavus*, *Botryosphaeria ribis*, *Colletotrichum gloeosporioides*, *F. oxysporum* and *Helminthosporium maydis* (Maksimov et al. 2011). Several species of bacteria belonging to genera *Bacillus* including *B. amyloliquefaciens* and *B. subtilis* were reported to reduce disease incidence in many host plants (Kloepper et al. 2007). Pseudomonad strains isolated from rice rhizosphere showed antagonism against phytopathogens such as *Colletotrichum capsici*, *C. falcatum*, *C. gleosporoides*, *Cylindrocladium floridanum*, *Cy. scoparium*, *Fusarium oxysporum* f. sp. *vasinfectum*, *Magnoporthe grisea*, *Macrophomina phaseolina*, *Pestalotia theae*, *Rhizoctonia solani* and *Sarocladium oryzae* in laboratory assays (Pathma et al. 2010). Chaoui et al. (2002) reported that vermicompost due to its non-thermophilic nature harbours diverse microbes of which a majority of them possess antagonism against soil-borne phytopathogenic fungus thereby aiding in biological control. *Pseudomonas corrugata* 214OR associated with *Aporrectodea trapezoids* and *A. rosea* suppressed *Gaeumannomyces graminis* var. *tritici* in wheat (Doube et al. 1994) (Table 9.2). Vermicompost application effectively controlled *F. oxysporum, F. proliferatum* (Moody et al. 1996; Szczech 1999), *Plasmodiophora brassicae* (Nakamura 1996); *Gaeumannomyces* sp. (Clapperton et al. 2001); *Verticillium* sp. (Chaoui et al. 2002); *Botrytis cineria* (Singh et al. 2008); *Pythium* sp. and *Rhizoctonia* sp. (Simsek et al. 2009). Elmer (2009) evidenced the suppression of *F. oxysporum* f. sp. *asparagi* and *F. proliferatum* in asparagus, *Verticillium dahlia* in eggplant and *F. oxysporum* f. sp. *lycopersic*i Race 1 in tomato by fluorescent pseudomonads and filamentous actinomycetes present in *L. terrestris* vermicompost. Actinobacteria, Bacteroidetes, Proteobacteria, Firmicutes and Verrucomicrobia isolated from *E. foetida* vermicompost showed antifungal activity against *Colletotrichum coccodes*, *F. moliniforme*, *P. capsici*, *P. ultimum* and *R. solani* (Yasir et al. 2009). About 49% of vermicompost bacteria isolated from the *E. foetida* vermicompost with a majority of them belonging to *Pseudomona*s and *Bacillus* evidenced strong antagonistic potential against various phytopathogenic fungus such as *Bipolaris oryzae*, *Colletotrichum gloeosporioides*, *Curvularia lunata*, *Cylindrocladium floridanum*, *C. scoparium*, *Fusarium oxysporum*, *Macrophomina phaseolina*, *Pestalotia theae* and *Sarocladium oryzae* in *in-vitro* assays (Pathma and Sakthivel 2013). Vermicompost bacteria *Pseudomonas* sp. FPVC5 exhibited broad-spectrum antifungal activity against phytopathogens such as *B. oryzae*, *C. floridanum*, *C. gloeosporioides, C. lunata*, *F. oxysporum*, *P. theae* and *S. oryzae* and while *Bacillus subtilis* BVC53 suppressed *C. floridanum*, *C. gloeosporioides*, *C. lunata*, *C. scoparium*, *F. oxysporum* and *M. phaseolina*. Majority of the vermicompost bacteria which exhibited antagonism produced proteases, cellulases, siderophores and HCN which were known to be prime factors involved in suppression of phytopathogenic fungi (Pathma and Sakthivel 2013) (Table 9.2).

Table 9.2 Disease suppression potential of vermicompost bacteria

Vermicompost bacteria	Pathogen suppressed	Disease	Crop	Reference
P. corrugate 214OR	*Gaeumannomyces graminis* var. *tritici*	Take-all disease	Wheat	Doube et al. (1994) and Clapperton et al. (2001)
Unknown antagonistic microbes	*Erysiphe cichoracearum*	Powdery mildew	Balsam	Singh et al. 2003
	E. pisi	Powdery mildew	Peas	
Unknown antagonistic microbes	*Pythium* sp.	Damping-off	Radish	Edwards et al. (2006)
	Rhizoctonia sp.	Damping-off/fruit rot	Cucumber	
	Verticillium sp.	Wilt	Strawberries	
	Phomopsis viticola	Phomopsis spot	Grapes	
	Erysiphe necator	Powdery mildew	Grapes	
	Erwinia tracheiphila	Bacterial rot	Cucumber	
Fluorescent pseudomonads, Filamentous actinomycetes, Bacilli	*Fusarium oxysporum* f. sp. *asparagi, F. proliferatum*	Wilt	Asparagus	Elmer (2009)
	F. oxysporum f. sp. *lycopersici* Race1	Wilt	Tomato	
	Verticillium dahlia	Wilt	Egg plant	
Nocardioides oleivorans, *Streptomyces griseinus*, *S. olivoviridis*, *S. praecox*, *S. pulveraceus*, *S. microflavus*, *S. globisporus*, *S. baarnensis*, *S. sindenensis*, *S. coelicolor*, *S. violascens*, *S. somaliensis*, *S. felleus*, *Staphylococcus epidermidis*	*Fusarium moniliforme*	Bakane disease	Rice	Yasir et al. (2009)
	Colletotrichum coccodes	Anthracnose	Tomato	
		Black dot	Potato	
	Phytophthora capsici	Blight/fruit rot	Solanaceous crops	
	Rhizoctonia solani	Sheath Blight	Rice	
		Bare patch	Cereals	
		Damping-off	Soyabean	
		Black scruf	Potatoes	
		Root rot	Beet root	
		Belly rot	Cucumber	
	Pythium ultimum	Damping-off/Root rot	Wheat, Corn, Soyabean, Potato	

(continued)

Table 9.2 (continued)

Vermicompost bacteria	Pathogen suppressed	Disease	Crop	Reference
Pseudomonas, Bacilli, *Acinetobacter*, *Microbacterium*, *Chryseobacterium*, *Arthrobacter*, *Enterobacter*, *Rheinheimera*, *Pseudoxanthomonas*, *Stenotrophomonas*, *Cellulomonas*, *Rhodococcus*	*Sarocladium oryzae*	Sheath rot	Paddy	Pathma and Sakthivel (2013)
	Bipolaris oryzae	Brown spot		
	Pestalothia theae	Leaf spot	Tea	
	Macrophomina phaseolina	Charcoal rot	Groundnut	
	Curvularia lunata	Leaf spot	Maize	
	Colletotrichum gloeosporioides	Anthracnose	Mango	
	Cylindrocladium floridanum, *Cy. scoparium*	Root necrosis	Banana	
	Fusarium oxysporum f. sp. *cubense*	Wilt		

9.4.3 Pests

Tomato plants treated with PGPR strains recorded significantly lower numbers of whitefly nymphs, the vectors of tomato mottle virus and thereby less disease incidence compared to untreated plants (Murphy et al. 2000). Cucumber plants treated with PGPR strains showed less infestation by spotted cucumber beetle *Diabrotica undecimpunctata* and hence showed less incidence of bacterial wilt in cucumber caused by *Erwinia tracheiphila*, vectored by cucumber beetles (Zehnder et al. 1997a, b). Development and fecundity of cotton aphid, *Aphis gossypii* on cucumber plant treated with *Bacillus pumilis* strain INR-7 was significantly reduced (Stout et al. 2002). Seed treatment done by combining two PGPR bacteria namely *Bacillus* sp. strain 6 and *Pseudomonas* sp. strain 6K reduced aphid population as well as improved productivity in bread wheat (Naeem et al. 2018). Application of different PGPR strains influenced the population of green peach aphid *Myzus persicae* (Boughton et al. 2006), blue-green aphid (*Acyrthosiphon kondoi* Shinji) on *Medicago* and white clover plants (Kempster et al. 2002). Application of vermicompost tea on cucumber seedlings suppressed the root penetration and hatching of root-knot nematode *Meloidogyne incognita* in field and laboratory trials (Mishra et al. 2017). Rhizobacterial strain *P. aeruginosa* caused mortality of nematodes (Gallagher and Manoil 2001) while strains of *Acinetobacter calcoaceticus*, *Aeromonas caviae*, *Alcaligenes latus*, *Arthrobacter* sp., *Bacillus* sp., *Chromobacterium* sp., *Corynebacterium urealyticum*, *Enterobacter gergoviae*, *Micrococcus*, *Neisseria*, *Rhizobium radiobacter* and *Serratia* were reported to possess lethal effects on termites *Odentotermes obesus* (Devi et al. 2006; Sindhu et al. 2011). Vermicompost application reduced the damage caused by hornworms (*Manduca quinquemaculata*), striped cucumber beetle (*Acalymma vittatum*), spotted cucumber beetle (*Diabotrica undecimpunctata*) in tomatoes in field and laboratory trails (Yardim et al. 2006). Addition of vermicompost decreased the incidence of defoliators namely *Apoaerema modicella*, *Helicoverpa armigera* and *Spodoptera litura* as well as sucking pests such as *Aphis craccivora* and *Empoasca kerri* and spider mites on groundnut under field conditions (Rao et al. 2001; Rao 2002, 2003); *Myzus persicae*, *Tetranychus* spp. (Edwards et al. 2007) and *Pseudococcus* spp. under greenhouse conditions (Arancon et al. 2007).

9.5 Mechanisms

9.5.1 Soil Fertility

Nitrogen, the most essential plant macronutrient though available in plenty in earth's atmosphere cannot be assimilated by plants as such. Certain microorganisms produce an enzyme nitrogenase which converts insoluble N_2 into NO_3^- and NH_4^+ that could be absorbed by plants by the process called biological N_2 fixation. Nitrogenase production is controlled by *nif* genes and the enzyme has two components, namely Fe protein and iron, molybdenum cofactor (Rees and Howard 2000; Dixon and

Kahn 2004). Majority of rhizosphere microorganisms as well as vermicompost bacteria are reported to be efficient nitrogen fixers and play an important role in slow and sustained release of nitrogen for better plant nutrition whereas inorganic nitrogenous fertilizer application releases nitrogen in an uncontrolled fashion and gives a lush green growth to plants favouring pest and disease incidence (Richardson et al. 2009; Pathma and Sakthivel 2012). Following nitrogen, phosphorous is the second major nutrient required for plants growth and development and it makes up 0.2% of the plants dry weight. Soil contains huge reserves of phosphorous but in forms that cannot be absorbed by the plants. Also, the inorganic phosphorous fertilizers we add to the soil gets quickly converted into plant insoluble forms adding to the soil pollution. Plant soluble forms of phosphorous include the $H_2PO_4^-$ (monobasic ion) and HPO_4^{2-} (diabasic ion) (Glass 1989). Microorganisms inhabiting soil especially the plant rhizosphere as well as those found in vermicompost are found to be efficient phosphate solubilizers (Ravindra et al. 2008; Pathma et al. 2010; Pathma and Sakthivel 2013; Alori et al. 2017). Microorganisms solubilize phosphorous through various mechanisms including acidification by secretion of organic acids or protons; chelation and exchange reactions (Hameeda et al. 2008; Richardson et al. 2009). Microbial phosphatase secreted by earthworm gut microflora caused phosphorous mineralization and mobilization and thereby increased the total phosphorous content in vermicompost. Vermicomposts application increases the ash content and hastens the mineralization rate and thus making nutrients available to plants. In addition, the earthworm gut microbes also increased the exchangeable forms of Ca^{2+}, Mg^{2+} and K^+ thereby supplementing plant nutrition (Zhang et al. 2000; Garg et al. 2006; Yasir et al. 2009). Soils supplemented with vermicompost or enriched with PGPR strains, exhibit a slow, sustained and balanced nutrition release pattern, especially those essential for plant growth such as plant available N, soluble K, exchangeable Ca, Mg and P due to its rich microflora (Edwards et al. 1998; Pathma and Sakthivel 2012, 2013). Root inoculation with PGPR strains namely *Azospirillum lipoferum*, *Azotobacter chroococcum*, *Bacillus megaterium* and *Pseudomonas fluorescens* increased chlorophyll and N, P, and K content of *Catharanthus roseus* (Lenin and Jayanthi, 2012).

9.5.2 Plant Growth Promotion

Rhizosphere microbiota plays an indispensable role in cycling plant nutrients such as C, N, P and S. Apart from providing essential nutrients in plant available forms they also produce many phytohormones such as IAA, cytokinins and gibberellins which stimulate and regulate the various physiological process and plant growth (Kloepper et al. 2007). IAA, gibberellins and cytokinins of microbial origin in significant quantities were detected in vermicompost which significantly improved plant growth (Atiyeh et al. 2002; Edwards et al. 2004; Pathma and Sakthivel 2012). IAA is involved in cell differentiation, root initiation, growth and abscission control (Beneduzi et al. 2008). Patten and Glick (2002) reported that auxins of microbial origin improved the plant root system enabling enhanced absorption of nutrients and water resulting in plant growth. Cytokinin is another important phytohormone secreted by microbes and it regulates cell division, enlargement, tissue enlargement and plant growth (Salisbury 1994). Microbially produced gibberellins influence plant growth and development (Arshad and Frankenberger 1993). Gibberellins are tetracarbocyclic diterpenes which interfere with cell division, cell elongation, increases fruit growth and interrupts dormancy thereby influencing plant growth (Beneduzi et al. 2008). Many rhizobacterial strains produce the enzyme ACC deaminase, which cleaves ACC, the precursor of ethylene and hinders ethylene production nullifying its detrimental effects on plant growth. Ethylene the gaseous phytohormone interferes with plant growth by affecting seed germination, fruit ripening, abscission of leaves, senescence of flowers and inhibits root growth (Salisbury 1994; Glick et al. 1998). Thus phytohormones produced by rhizosphere and vermicompost bacteria influence plant growth directly or indirectly at different stages.

9.5.3 Pathogen Suppression

The rhizosphere, as well as vermicompost microbes, adopt several mechanisms to fight plant pathogens which include antibiosis due to production of metabolites such as antibiotics, siderophores and hydrogen cyanide (HCN) (Lugtenberg and Kamilova 2009; Raaijmakers et al. 2009; Ambrosini and Beneduzi 2012); competition for microsites, nutrients and trace elements (Duffy 2001), parasitism (Mela et al. 2011); production of cell-wall degrading enzymes (Pal and Gardener 2006; Mabood et al. 2014); affecting virulence by intervening quorum sensing (Lin et al. 2003; Uroz et al. 2009; Chen et al. 2011) and induced systemic resistance (Conrath 2006; Pieterse 2012; Schenk et al. 2012). Many strains of rhizobacteria and vermicompost bacteria have been reported to produce antifungal metabolites such as pyrrolnitrin, 2,4-diacetylphloroglucinol, oomycin A, pyocyanin, pyrroles, pyoluteorin, pantocin, viscosinamide, mupirocin, pyrrolnitrin, iturins, bacillomycin, surfactin, zwittermicin A, HCN, phenazines and tensin (Nielsen et al. 2002; Pathma et al. 2011; Pathma and Sakthivel 2012; Bhattacharyya and Jha 2012; Shaikh et al. 2016). Also, production of HCN, a volatile compound with antibiotic properties by rhizosphere and vermicompost bacteria such as *Pseudomonas* and *Bacillus* were reported to be an important mechanism responsible for antagonism against soil-borne phytopathogenic fungus (Wahyudi et al. 2011; Pathma and Sakthivel 2013). Siderophores are low molecular weight iron chelating ligand produced by microbes and plays an important role in plant nutrition and disease suppression, especially in iron deficit soils. Rhizospheric bacteria are evidenced to produce a wide array of siderophores including pseudobactin, pyoverdines, and pyochelin by pseudomonads; schizokinen by *Bacillus megaterium*; dihydroxybenzoic acid derivatives by *B. subtilis* and *Pseudomonas stutzeri*; ferrioxamine and arthrobactin by *Arthrobacter* spp.; Enterobactin by *Enterobacter* and mycobactins by *Rhodococcus* sp. These bacterial siderophores compete with phytopathogenic fungus for iron in iron deficit soils and make them unavailable for the phytopathogens thereby hampers their growth (Crowley 2006). Pathma and Sakthivel (2013) documented the production of siderophores by nearly 50% of vermicompost bacteria and the majority of them showed antagonism against tested phytopathogens. Microbial cell-wall lysis by cell wall degrading enzymes is the main feature of mycoparasitism. Chitinase, β-1,3-glucanase, protease and cellulase are important fungal cell-wall degrading enzymes that suppress fungal growth (Chernin et al. 1995; Dunn et al. 1997; Ravindra et al. 2008). Nielsen and Sorensen (1997) reported, *Bacillus* sp., *B. pumilus* and *Paenibacillus polymyxa* with gluconolytic and proteolytic enzymes active against plant-pathogenic microfungi such as *Aphanomyces cochleoides, P. ultimum* and *R. solani* from barley rhizosphere. Majority of rhizobacteria and vermicompost bacteria produce extracellular fungal cell-wall degrading enzymes such as proteases, lipases, DNases, chitinases and glucanases which play a major role in the control of phytopathogenic fungus with an exception of those belonging to oomycetes (Maksimov et al. 2011; Shaikh and Sayyed 2015). *Bacillus* spp. produced an array of enzymes such as cellulase, hemicellulase, xylanase and mannanase which effectively degraded cellulose, galactomannan or mannoprotein containing cell walls of oomycetes (Bartnicki-Garcia 1987; Kim and Kim 1993). Vivekananthan et al. (2004) documented the role of microbial chitinase and β-1,3-glucanase in control of *Colletotrichum gloeosporioides*. Frankowski et al. (2001) reported that chitinase from *Serratia plymuthica* C48 inhibited spore germination and germ tube elongation in *Botrytis cinerea.* Chitinolytic bacterial communities isolated from vermicompost including *Nocardioides oleivorans*, *Staphylococcus epidermidis* and *Streptomyces* spp. showed deleterious effects against phytopathogens namely *C. coccodes*, *F. moniliforme*, *P. capsici*, *P. ultimum* and *R. solani* (Yasir et al. 2009). Scientific investigations evidenced that the majority of the vermicompost bacteria with antagonistic potential also produced lytic enzymes such as protease, cellulase, DNase, xylanase and amylase (Pathma and Sakthivel 2013).

Suppression of black root rot of tobacco caused by *Thielaviopsis basicola* and take-all disease of wheat caused by *Gaeumannomyces graminis* var. tritici was due to HCN from *P. fluorescens* CHA0 (Voisard et al. 1981). Ahmad et al. (2005) reported that HCN from *Pseudomonas* and *Bacillus* played an indispensable role in their antifungal activity against many phytopathogenic fungi. O'Sullivan and O'Gara (1992) reported that disease suppression by HCN producing fluorescent pseudomonads may be partly due to the induction of plant resistance. Interaction with PGPR strains trigger induced systemic resistance (ISR) in plants which protects them from diseases caused by pathogenic bacteria, fungi and viruses. Bacterial components such as flagella, lipopolysaccharides (LPS), siderophores, cyclic lipopeptides, 2,4-diacetylphloroglucinol, homoserine lactones, acetoin and 2,3-butanediol induce systemic resistance (ISR) which involve jasmonate and ethylene signalling thereby stimulating the host plants defense mechanisms (Lugtenberg and Kamilova 2009; Glick 2012).

9.5.4 Pest Control

PGPR strains induce resistance against arthropods by phytohormones synthesis, increase in solubility and uptake of phosphorus, nitrogen, iron and other essential minerals through chelation growth (Bowen and Rovira 1999). PGPR-treated cucumber showed reduced concentrations of a plant secondary metabolite cucurbitacin, which is a feeding stimulant and thereby reduces the palatability of the host plant to cucumber beetle. In addition, PGPR treatment elicits the Induced systemic resistance (ISR) in cucumber plants resulting in a significant decrease in feeding damage by cucumber beetle (Zehnder et al. 1997a, b). Reduction in damage of tomato plants by coleopterans namely *Acalymma vittatum* and *Diabotrica undecimpunctata* and lepidopteran *Manduca quinquemaculata* by vermicompost application are due to the induction of biological resistance by the interaction of vermicompost bacteria (Yardim et al. 2006; Sinha et al. 2010). Mishra et al. (2017) stated that suppression of *Meloidogyne incognita* in cucumber by vermicompost tea application is possibly due to induction of host plant resistance. Hydrolytic enzymes such as chitinases and proteases secreted by beneficial microbes causes hydrolysis of nematode eggs while the antibiotics produced by the beneficial bacteria adversely affects nematode penetration into host root. HCN produced from rhizobacterial strains inhibited the respiratory enzymes leading to the mortality of nematodes and termites (Gallagher and Manoil 2001; Devi et al. 2006). Devi and David (2009) reported that *Pseudomonas fluorescens* CHA0 suppressed the growth of *Odontermes obesus* by inhibiting cytochrome cooxidase of termite respiratory chain. The microbial consortia of vermicompost and the mechanisms of slow nutrient release pattern, as well as the phenolic content of the vermicompost play a vital role in offering pest resistance.

9.6 Conclusion

Intensive cropping due to the increase in human population and shrinkage of land has led to the deterioration of soil fertility. Use of agrochemicals in the form of fertilizers and plant protection agents have added to the problem by destroying the soil microbial diversity which are the key indicators of soil health and sustainability. Amelioration of degraded soil is the need of the hour and enriching the soil microflora is the only way for soil remediation and reduction of environmental pollution. Application of organic material such as vermicomposts which are rich in microbial population and diversity and need-based application of PGPR strains could alleviate the problems of soil pollution and improve soil fertility and productivity. Thus, knowledge on microbiome of rhizospheric soil and vermicompost will help us in decision making for efficient management of soil productivity by enriching the soil beneficial microbes for sustainable agriculture.

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References

Ahemad M, Kibret M (2014) Mechanisms and applications of plant growth promoting rhizobacteria: current perspective. J King Saud Univ Sci 26:1–20

Ahmad F, Ahmad I, Khan MS (2005) Indole acetic acid production by the indigenous isolates of *Azotobacter* and fluorescent Pseudomonas in the presence and absence of tryptophan. Turk J Biol 29:29–34

Alori ET, Glick BR, Babalola OO (2017) Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Front Microbiol 8:1–8

Ambrosini A, Beneduzi A (2012) Screening of plant growth promoting rhizobacteria isolated from sunflower (*Helianthus annuus* L.). Plant Soil 356:245–264

Arancon NQ, Edwards CA, Yardim EN, Oliver TJ, Byrne RJ, Keeney G (2007) Suppression of two-spotted spider mite (*Tetranychus urticae*), mealy bug (*Pseudococcus* sp.) and aphid (*Myzus persicae*) populations and damage by vermicomposts. Crop Prot 26:29–39

Arshad M, Frankenberger WT Jr (1993) Microbial production of plant growth regulators. In: Metting FB Jr (ed) Soil microbial ecology: applications in agricultural and environmental management. Marcell Dekker, New York/Basel/Hong Kong, pp 307–347

Asghar HN, Zahir ZA, Arshad M, Khaliq A (2002) Relationship between in vitro production of auxins by rhizobacteria and their growth promoting activities in *Brassica juncea* L. Biol Fertil Soils 35:231–237

Atiyeh RM, Lee S, Edwards CA, Arancon NQ, Metzger JD (2002) The influence of humic acids derived from earthworm-processed organic wastes on plant growth. Bioresour Technol 84:7–14

Baca BE, Elmerich C (2007) Microbial production of plant hormones. In: Elmerich C, Newton WE (eds) Associative and endophytic nitrogen-fixing bacteria and cyanobacterial associations. Springer, Dordrecht, pp 113–143

Badenosch-Jones J, Summons RE, Djordjevic MA, Shine J, Letham DS, Rolfe BG (1982) Mass-spectrometric quantification of indole-3-acetic acid in culture supernatants of *Rhizobium* strains, studies in relation to root hair curling and nodule initiation. Appl Environ Microbiol 44:275–280

Barriuso J, Solano BR, Lucas JA, Lobo AP, García-Villaraco A, Mañero FJG (2008) Ecology, genetic diversity and screening strategies of plant growth promoting rhizobacteria (PGPR). In: Ahmad I, Pichtel J, Hayat S (eds) Plant-bacteria interactions. Strategies and techniques to promote plant growth. Wiley-VCH, Weinheim, pp 1–17

Bartnicki-Garcia S (1987) The cell wall: a crucial structure in fungal evolution. In: Rayner ADA, Brasier CM, Moore D (eds) Evolutionary biology of the fungi. Cambridge University Press, New York, pp 390–403

Belimov AA, Safronova VI, Sergeyeva TA, Egorova TN, Matveyeva VA, Tsyganov VE, Borisov AY, Tikhonovich IA, Kluge C, Preisfeld A, Dietz KJ, Stepanok VV (2001) Characterization of plant growth promoting rhizobacteria isolated from polluted soils containing 1-aminocyclopro pane-1-carboxylate deaminase. Can J Microbiol 47:642–652

Beneduzi A, Peres D, da Costa PB, Zanettini MHB, Passagli LMP (2008) Genetic and phenotypic diversity of plant growth-promoting bacilli isolated from wheat fields in southern Brazil. Res Microbiol 159:244–250

Berendsen RL, Pieterse CM, Bakker PA (2012) The rhizosphere microbiome and plant health. Trends Plant Sci 17:478–486

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Boughton AJ, Hoover K, Felton GW (2006) Impact of chemical elicitor applications on greenhouse tomato plants and population growth of the green peach aphid, *Myzus persicae*. Entomol Exp Appl 120:175–188

Bowen GD, Rovira AD (1999) The rhizosphere and its management to improve plant growth. Adv Agron 66:1–102

Braga LPP, Yoshiura CA, Borges CD, Horn MA, Brown GG, HL D, Tsai SM (2016) Disentangling the influence of earthworms in sugarcane rhizosphere. Sci Rep 6:38923
Byrne JM, Dianes AC, Ji P, Campbella HL, Cuppels DA, Louws FJ, Millerd SA, Jones JB, Wilson M (2005) Biological control of bacterial spot of tomato under field conditions at several locations in North America. Biol Control 32(3):408–418
Cao Y, Fu D, Liu T, Guo G, Hu Z (2018) Phosphorus solubilizing and releasing bacteria screening from the rhizosphere in a natural wetland. Water 195:1–15
Cassan FD, Bottini R, Piccoli P (2001) *In vivo* gibberellin A metabolism by *Azospirillum* sp. in *dy* dwarf rice mutant seedlings. Proc Plant Growth Reg 28:124–129
Chaoui H, Edwards CA, Brickner M, Lee S, Arancon N (2002) Suppression of the plant diseases, *Pythium* (damping off), *Rhizoctonia* (root rot) and *Verticillum* (wilt) by vermicomposts. In: Proceedings of Brighton crop protection conference – pests and diseases, vol II (8B-3), pp 711–716
Chen KG, Atkinson S, Mathee K et al (2011) Characterization of N-acylhomoserine lactone-degrading bacteria associated with the *Zingiber officinale* (ginger) rhizosphere: co-existence of quorum quenching and quorum sensing in *Acinetobacter* and *Burkholderia*. BMC Microbiol 11:51
Chernin I, Ismailov Z, Haran S, Chet I (1995) Chitinolytic Enterobacter agglomerans antagonistic to fungal plant pathogens. Appl Environ Microbiol 61:1720–1726
Citernesi U, Neglia R, Seritti A, Lepidi AA, Filippi C, Bagnoli G, Nuti MP, Galluzzi R (1977) Nitrogen fixation in the gastro-enteric cavity of soil animals. Soil Biol Biochem 9:71–72
Clapperton MJ, Lee NO, Binet F, Conner RL (2001) Earthworms indirectly reduce the effect of take-all (*Gaeumannomyces graminis* var. *tritici*) on soft white spring wheat (*Triticium aestivum* cv. Fielder). Soil Biol Biochem 33:1531–1538
Compant S, Clément C, Sessitsch A (2010) Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. Soil Biol Biochem 42:669–678
Conrath U (2006) Systemic acquired resistance. Plant Signal Behav 4:179–184
Crowley DE (2006) Microbial siderophores in the plant rhizosphere. In: Barton LL, Abadía J (eds) Iron nutrition in plants and rhizospheric microorganisms. Springer, Amsterdam, pp 169–198
Das R, Mondal B, Mondal P, Khatua DC, Mukherjee N (2014) Biological management of citrus canker on acid lime through *Bacillus subtilis* (S-12) in West Bengal, India. J Biopest 7:38–41
Delfim J, Schoebitz M, Paulino L, Hirzel J, Zagal E (2018) Phosphorus availability in wheat, in volcanic soils inoculated with phosphate-solubilizing *Bacillus thuringiensis*. Sustainability 10:144
Devi KK, David K (2009) *Pseudomonas fluorescens* CHA0 can kill subterranean termite *Odontotermes obesus* by inhibiting cytochrome coxidase of the termite respiratory chain. FEMS Microbiol Lett 300:195–200
Devi KK, Seth N, Kothamasi S, Kothamasi D (2006) Hydrogen cyanide-producing rhizobacteria kill subterranean termite *Odontotermes obesus* (Rambur) by cyanide poisoning under in vitro conditions. Curr Microbiol 54:74–78
Dixon R, Kahn D (2004) Genetic regulation of biological nitrogen fixation. Nat Rev Microbiol 2:621–631
Doube BM, Stephens PM, Davorena CW, Ryderb MH (1994) Interactions between earthworms, beneficial soil microorganisms and root pathogens. Appl Soil Ecol 1:3–10
Duffy BK (2001) Competition. In: Maloy OC, Murray TD (eds) Encyclopedia of plant pathology. Wiley, New York, pp 243–244
Dunn C, Crowley JJ, Moenne-Loccoz Y, Dowling DN, de Bruijn FJ, O'Gara F (1997) Biological control of Pythium ultinum by *Stenotrophomonas maltophilia* W18 is mediated by an extracellular proteolytic activity. Microbiology 143:3921–3931
Edwards CA, Dominguez J, Neuhauser EF (1998) Growth and reproduction of *Perionyx excavatus* (Perr.) (Megascolecidae) as factors in organic waste management. Biol Fertil Soils 27:155–161

Edwards CA, Dominguez J, Arancon NQ (2004) The influence of vermicomposts on pest and diseases. In: Shakir Hanna SH, WZA M (eds) Soil zoology for sustainable development in the 21st century. Geocities, Cairo, pp 397–418

Edwards CA, Arancon NQ, Greytak S (2006) Effects of vermicompost teas on plant growth and disease. BioCycle 45:28–29

Edwards CA, Arancon NQ, Emerson E, Pulliam R (2007) Suppressing plant parasitic nematodes and arthropod pests with vermicompost teas. BioCycle 48(12):38–39

Elmer WH (2009) Influence of earthworm activity on soil microbes and soilborne diseases of vegetables. Plant Dis 93:175–179

Figueiredo MVB, Seldin L, De Araujo FF, De Mariano RLR (2010) Plant growth promoting rhizobacteria: fundamentals and applications. In: Maheshwari DK (ed) Plant growth and health promoting bacteria, Microbiol monographs 18. Springer, Heidelberg/New York, pp 21–43

Frankowski J, Lorito M, Scala F, Schmid R, Berg G, Bahl H (2001) Purification and properties of two chitinolytic enzymes of *Serratia plymuthica* HRO-C48. Arch Microbiol 176(6):421–426

Fulchieri M, Lucangeli C, Bottini R (1993) Inoculation with *A. lipoferum* affects growth and gibberellin status of corn seedlings roots. Plant Cell Physiol 34:1305–1309

Gallagher LA, Manoil C (2001) *Pseudomonas aeruginosa* PAO1 kills *Caenorhabditis elegans* by cyanide poisoning. J Bacteriol 183:6207–6214

Garcia de Salamone IE, Hynes RK, Nelson LM (2001) Cytokinin production by plant growth-promoting rhizobacteria and selected mutants. Can J Microbiol 47:404–411

Garg P, Gupta A, Satya S (2006) Vermicomposting of different types of waste using *Eisenia foetida*: a comparative study. Bioresour Technol 97:391–395

Glass ADM (1989) Plant nutrition: an introduction to current concepts. Jones and Bartlett, Boston, p 234

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012:963401

Glick BR, Penrose DM, Li J (1998) A model for the lowering of plant ethylene concentrations by plant growth promoting bacteria. J Theor Biol 190:63–68

Gopal M, Gupta A, Sunil E, Thomas VG (2009) Amplification of plant beneficial microbial communities during conversion of coconut leaf substrate to vermicompost by *Eudrilus* sp. Curr Microbiol 59:15–20

Hameeda B, Harini G, Rupela OP, Wani SP, Reddy G (2008) Growth promotion of maize by phosphate-solubilizing bacteria isolated from composts and macrofauna. Microbiol Res 163:234–242

Hayat R, Ahmed I, Sheirdil RA (2012) An overview of plant growth promoting rhizobacteria (PGPR) for sustainable agriculture. In: Ashraf M, Oztürk M, Ahmad MSA, Aksoy A (eds) Crop production for agricultural improvement. Springer, Berlin, pp 557–579

Karsten GR, Drake HL (1997) Denitrifying bacteria in the earthworm gastrointestinal tract and in vivo emission of nitrous oxide (N_2O) by earthworms. Appl Environ Microbiol 63:1878–1882

Kawasaki A, Donn S, Ryan PR, Mathesius U, Devilla R, Jones A et al (2016) Microbiome and exudates of the root and rhizosphere of *Brachypodium distachyon,* a model for wheat. PLoS ONE 11(10):e0164533

Kempster VN, Scott ES, Davies KA (2002) Evidence for systemic, cross-resistance in white clover (*Trifolium repens*) and annualmedic (*Medicago truncatula* var. truncatula) induced bybiological and chemical agents. Biocontrol Sci Tech 12:615–623

Kim HJ, Jeun YC (2006) Resistance induction and enhanced tuber production by pre-inoculation with bacterial strains in potato plants against *Phytophthora infestans*. Mycobiology 34(2):67–72

Kim CH, Kim DS (1993) Extracellular cellulolytic enzymes of *Bacillus circulans* are present as two multiple-protein complexes. Appl Biochem Biotechnol 42:83–94

Kim CH, Han SH, Kim KY, Cho BH, Kim YH, Koo BS, Kim YC (2004) Cloning and expression of pyrroloquinoline quinone (PQQ) genes from a phosphate-solubilizing bacterium *Enterobacter intermedium*. Curr Microbiol 47:6

Kloepper JW, Leong J, Teintze M, Schroth MN (1980) Enhanced plant growth by siderophores produced by plant growth promoting rhizobacteria. Nature 286:885–886

Kloepper JW, Gutierrez-Estrada A, Mclnroy JA (2007) Photoperiod regulates elicitation of growth promotion but not induced resistance by plant growth-promoting rhizobacteria. Can J Microbiol 53:159–167

Krause MS, DeCeuster TJJ, Tiquia SM, Michel FC Jr, Madden LV, Hoitin HAJ (2003) Isolation and characterization of rhizobacteria from compost that suppress the severity of bacterial leaf spot of radish. Phytopathology 93:1292–1300

Krishnamoorthy RV, Vajranabhiah SN (1986) Biological activity of earthworm casts: an assessment of plant growth promoter levels in casts. Proc Indian Acad Sci (Anim Sci) 95:341–335

Lebuhn M, Heulin T, Hartmann A (1997) Production of auxin and other indolic and phenolic compounds by *Paenibacillus polymyxa* strains isolated from different proximity to plant roots. FEMS Microbiol Ecol 22:325–334

Lenin G, Jayanthi M (2012) Efficiency of plant growth promoting rhizobacteria (PGPR) on enhancement of growth, yield and nutrient content of *Catharanthus roseus*. Int J Res Pure Appl Microbiol 2:37–42

Lin YH, Xu JL, Hu J, Wang LH, Ong SL, Leadbetter JR, Zhang LH (2003) Acyl-homoserine lactone acylase from *Ralstonia* strain XJ12B represents a novel and potent class of quorum-quenching enzymes. Mol Microbiol 47:849–860

Liu L, Kloepper JW, Tuzun S (1995) Induction of systemic resistance in cucumber against bacterial leaf spot by plant growth promoting rhizobacteria. Phytopathology 85:843–847

Lopez MM, Gorris MT, Salcedo CI, Montojo AM, Miro M (1989) Evidence of biological control of *Agrobacterium tumefaciens* strains sensitive and resistant to agrocin 84 by different *Agrobacterium radiobacter* strains on stone fruit trees. Appl Environ Microbiol 55(3):741–746

Lugtenberg B, Kamilova F (2009) Plant-growth-promoting rhizobacteria. Annu Rev Microbiol 63:541–556

Mabood F, Zhou X, Smith DL (2014) Microbial signaling and plant growth promotion. Can J Plant Sci 94:1051–1063

Madsen EL, Alexander M (1982) Transport of rhizobium and Pseudomonas through soil. Soil Sci Soc Am J 46:557–560

Maksimov IV, Abizgil RR, Pusenkova LI (2011) Plant growth promoting rhizobacteria as alternative to chemical crop protectors from pathogens (review). Appl Biochem Microbiol 47(4):373–385

Mela F, Fritsche K, de Boer W, van Veen JA, de Graaff LH, van den Berg M, Leveau JHJ (2011) Dual transcriptional profiling of a bacterial/fungal confrontation: *Collimonas fungivorans* versus *Aspergillus niger*. ISME J 5:1494–1504

Mishra S, Wang K, Sipes BS, Tian M (2017) Suppression of root-knot nematode by vermicompost tea prepared from different curing ages of vermicompost. Plant Dis 101(5):734–737

Moody SA, Piearce TG, Dighton J (1996) Fate of some fungal spores associated with wheat straw decomposition on passage through the guts of *Lumbricus terrestris* and *Aporrectodea longa*. Soil Biol Biochem 28:533–537

Moore TC (1989) Auxins. In: Biochemistry and physiology of plant hormones. Springer, New York, pp 27–33

Murphy JF, Zehnder GW, Schuster DJ, Sikora EJ, Polston JE, Kloepper JW (2000) Plant growth-promoting rhizobacterial mediated protection in tomato against tomato mottle virus. Plant Dis 84:779–784

Naeem M, Aslam Z, Khaliq A, Ahmed JN, Nawaz A, Hussain M (2018) Plant growth promoting rhizobacteria reduce aphid population and enhance the productivity of bread wheat. Environ Microbiol. https://doi.org/10.1016/j.bjm.2017.10.005

Nakamura Y (1996) Interactions between earthworms and microorganisms in biological control of plant root pathogens. Farming Jpn 30:37–43

Nielsen P, Sorensen J (1997) Multi-target and medium-independent fungal antagonism by hydrolytic enzymes in *Paenibacillus polymyxa* and *Bacillus pumilus* strains from barley rhizosphere. FEMS Microbiol Ecol 22:183–192

Nielsen TH, Sorensen D, Tobiasen C, Andersen JB, Christeophersen C, Givskov M, Sorensen J (2002) Antibiotic and biosurfactant properties of cyclic lipopeptides produced by fluorescent *Pseudomonas* spp. from the sugar beet rhizosphere. Appl Environ Microbiol 68:3416–3423

Oliveira CA, Alves VMC, Marriel IE, Gomes EA, Scotti MR, Carneiro NP, Guimarães CT, Schaffert RE, Sá NMH (2009) Phosphate solubilizing microorganisms isolated from rhizosphere of maize cultivated in an oxisol of the Brazilian Cerrado Biome. Soil Biol Biochem 41:1782–1787

O'Sullivan D, O'Gara F (1992) Traits of fluorescent *Pseudomonas* spp. involved in suppression of plant root pathogens. Microbiol Rev 56:662–676

Ozaktan H, Bora T (2004) Biological control of fire blight in pear orchards with a formulation of *Pantoea agglomerans* strain Eh 24. Braz J Microbiol 35:224–229

Pal KK, Gardener BM (2006) Biological control of plant pathogens. Plant Health Instructor:1–25. https://doi.org/10.1094/phi-a-2006-1117-02

Pathma J, Sakthivel N (2012) Microbial diversity of vermicompost bacteria that exhibit useful agricultural traits and waste management potential. SpringerPlus 1(1):1–19

Pathma J, Sakthivel N (2013) Molecular and functional characterization of bacteria isolated from straw and goat manure based vermicompost. Appl Soil Ecol 70:33–47

Pathma J, Ayyadurai N, Sakthivel N (2010) Assessment of genetic and functional relationship of antagonistic fluorescent pseudomonads of rice rhizosphere by repetitive sequence, protein coding sequence and functional gene analyses. J Microbiol 48:715–727

Pathma J, Rahul GR, Kamaraj Kennedy R, Subashri R, Sakthivel N (2011) Secondary metabolite production by bacterial antagonists. J Biol Control 25:165–181

Patten CL, Glick BR (2002) Role of *Pseudomonas putida* indole acetic acid in development of the host plant root system. Appl Environ Microbiol 68:3795–3801

Pieterse CMJ (2012) Prime time for transgenerational defense. Plant Physiol 158:545

Pliego C, Kamilova F, Lugtenberg B (2011) Plant growth-promoting bacteria: fundamentals and exploitation. In: Maheshwari DK (ed) Bacteria in agrobiology: crop ecosystems. Springer, Berlin, pp 295–343

Qiao Q, Wang F, Zhang J, Chen Y, Zhang C, Liu G, Zhang H, Ma C, Zhang J (2017) The variation in the rhizosphere microbiome of cotton with soil type, genotype and developmental stage. Sci Rep 7:3940

Raaijmakers JM, Paulitz TC, Steinberg C, Alabouvette C, Moenne-Loccoz Y (2009) The rhizosphere: a playground and battlefield for soilborne pathogens and beneficial microorganisms. Plant Soil 321:341–361

Rao KR (2002) Induce host plant resistance in the management sucking pests of groundnut. Ann Plant Protect Sci 10:45–50

Rao KR (2003) Influence of host plant nutrition on the incidence of *Spodoptera litura* and *Helicoverpa armigera* on groundnuts. Indian J Entomol 65:386–392

Rao KR, Rao PA, Rao KT (2001) Influence of fertilizers and manures on the population of coccinellid beetles and spiders in groundnut ecosystem. Ann Plant Protect Sci 9:43–46

Rashid MH, Krehenbrink M, Akhtar MS (2015) Nitrogen-fixing plant-microbe symbioses. In: Lichtfouse E (ed) Sustainable agriculture reviews, vol 15. Springer, Cham, pp 193–234

Ravindra NP, Raman G, Badri Narayanan K, Sakthivel N (2008) Assessment of genetic and functional diversity of phosphate solubilizing fluorescent pseudomonads isolated from rhizospheric soil. BMC Microbiol 8:230

Rees DC, Howard JB (2000) Nitrogenase: standing at the crossroads. Curr Opin Chem Biol 4:559–566

Richardson AE, Barea JM, McNeill AM, Prigent-Combaret C (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant Soil 321:305–339

Rouelle J (1983) Introduction of an amoeba and *Rhizobium japonicum* into the gut of *Eisenia foetida* (Sav.) and *Lumbricus terrestris* L. In: Satchell JE (ed) Earthworm ecology: from Darwin to vermiculture. Chapman and Hall, New York, pp 375–381

Saharan BS, Nehra V (2011) Plant growth promoting rhizobacteria: a critical review. Life Sci Med Res 21:1–30

Salisbury FB (1994) The role of plant hormones plant environment interactions. In: Wilkinson RE (ed) Plant environment interactions. Marcel Dekker, New York, pp 39–81

Schenk ST, Stein E, Kogel KH, Schikora A (2012) *Arabidopsis* growth and defense are modulated by bacterial quorum sensing molecules. Plant Signal Behav 7:178–181

Schulz K, Hunger S, Brown GG, Tsai SM, Cerri CC, Conrad R, Drake HL (2015) Methanogenic food web in the gut contents of methane-emitting earthworm *Eudrilus eugeniae* from Brazil. ISME J 9:1778–1792

Shaikh SS, Sayyed RZ (2015) Role of plant growth-promoting rhizobacteria and their formulation in biocontrol of plant diseases. In: Plant microbes Symbiosis: applied facets

Shaikh SS, Sayyed RZ, Reddy MS (2016) Plant growth-promoting rhizobacteria: an eco-friendly approach for sustainable agroecosystem. In: Hakeem KR et al (eds) Plant, soil and microbes. Springer, Cham

Simsek EY, Haktanir K, Yanar Y (2009) Vermicompost suppresses *Rhizoctonia solani* Kühn in cucumber seedlings. J Plant Dis Protect 9:15–17

Sindhu SS, Rakshiya YS, Verma MK (2011) Biological control of termites by antagonistic soil microorganisms. In: Singh A et al (eds) Bioaugmentation, biostimulation and biocontrol, soil biology. Springer, Berlin/Heidelberg

Singh UP, Maurya S, Singh DP (2003) Antifungal activity and induced resistance in pea by aqueous extract of vermicompost and for control of powdery mildew of pea and balsam. J Plant Dis Protect 110:544–553

Singh R, Sharma RR, Kumar S, Gupta RK, Patil RT (2008) Vermicompost substitution influences growth, physiological disorders, fruit yield and quality of strawberry (*Fragaria xananassa* Duch.). Bioresour Technol 99:8507–8511

Sinha RK, Valani D, Chauhan K, Agarwal S (2010) Embarking on a second green revolution for sustainable agriculture by vermiculture biotechnology using earthworms: reviving the dreams of Sir Charles Darwin. J Agric Biotech Sustain Dev 2(7):113–128

Srinivasan M, Holl FB, Petersen DJ (1996) Influence of indoleacetic-acid-producing *Bacillus* isolates on the nodulation of *Phaseolus vulgaris* by *Rhizobium etli* under gnotobiotic conditions. Can J Microbiol 42:1006–1014

Stephens PM, Davoren CW, Ryder MH, Doube BM (1994) Influence of the earthworm *Aporrectodea trapezoides* (Lumbricidae) on the colonization of alfalfa (*Medicago sativa* L.) roots by *Rhizobium melilotti* strain LS-30R and the survival of L5-30R in soil. Biol Fertil Soils 18:63–70

Stout MJ, Zehnder GW, Baur ME (2002) Potential for the use of elicitors of plant defense in arthropod management programs. Arch Insect Biochem 51:222–235

Suhane RK (2007) Vermicompost. Publication of Rajendra Agriculture University, Pusa, p 88

Sumathi G, Thaddeus A (2013) Impact of organic rich diet on gut enzymes, microbes and biomass of earthworm, *Eudrilus eugienea*. J Environ Biol 34:515–520

Szczech MM (1999) Suppressiveness of vermicomposts against fusarium wilt of tomato. J Phytopathol 147:155–161

Tao GC, Tian SJ, Cai MY, Guang HX (2008) Phosphate-solubilizing and -mineralizing abilities of bacteria isolated from soils. Pedosphere 4:515–523

Tien TM, Gaskins MH, Hubell DH (1979) Plant growth substances produced by *Azospirillum brasilense* and their effect on the growth of pearl millet (*Pennisetum americanum* L). Appl Environ Microbiol 37:1016–1024

Tomati U, Grapppelli A, Galli E (1988) The hormone-like effect of earthworm casts on plant growth. Biol Fertil Soils 5:288–294

Torino CM, Lerios TE, Bretana BLP (2013) Isolation and characterization of cellulose-degrading bacteria of African night crawler (*Eudrilus eugeniae* Kinberg). USM R&D Journal 29:49–54

Uroz S, Dessaux Y, Oger P (2009) Quorum sensing and quorum quenching: the yin and yang of bacterial communication. ChemBioChem 10:205–216

Vaz-Moreira I, Silva ME, Manaia CM, Nunes OC (2008) Diversity of bacterial isolates from commercial and homemade composts. Microb Ecol 55:714–722

Vega NWO (2007) A review on beneficial effects of rhizosphere bacteria on soil nutrient availability and plant nutrient uptake. Rev Fac Nac Agron Medellín 60:1

Vega HB, Victoria DE (2009) Bacterial diversity in the digestive tract of earthworms (Oligochaeta). J Biol Sci 9:192–199

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Villegas J, Fortin JA (2001) Phosphorus solubilization and pH changes as a result of the interactions between soil bacteria and arbuscular mycorrhizal fungi on a medium containing NO_3-as nitrogen source. Can J Bot 80:571–576

Vivas A, Moreno B, Garcia-Rodriguez S, Benitez E (2009) Assessing the impact of composting and vermicomposting on bacterial community size and structure, and functional diversity of an olive-mill waste. Bioresour Technol 100(3):1319–1326

Vivekananthan R, Ravi M, Ramanathan A, Samiyappan R (2004) Lytic enzymes induced by *Pseudomonas fluorescens* and other biocontrol organisms mediate defence against the anthracnose pathogen in mango. World J Microbiol Biotechnol 20(3):235–244

Voisard C, Keel C, Haas D, Defago G (1981) Cyanide production in *Pseudomonas fluorescens* helps suppress black root rot of tobacco under gnotobiotic conditions. EMBO J 8:351–358

Wahyudi A, Astuti RP, Widyawati A, Meryandini A, Nawangsih AA (2011) Characterization of *Bacillus* sp., strains isolated from rhizosphere of soybean plants for their use as potential plant growth for promoting rhizobacteria. J Microbiol Antimicrobials 3:34–40

Yardim EN, Arancon NQ, Edwards CA, Oliver TJ, Byrne RJ (2006) Suppression of tomato hornworm (*Manduca quinquemaculata*) and cucumber beetles (*Acalymma vittatum* and *Diabotrica undecimpunctata*) populations and damage by vermicomposts. Pedobiologia 50:23–29

Yasir M, Aslam Z, Kim SW, Lee SW, Jeon CO, Chung YR (2009) Bacterial community composition and chitinase gene diversity of vermicompost with antifungal activity. Bioresour Technol 100:4396–4403

Zakharova E, Shcherbakov A, Brudnik V, Skripko N, Bulkhin N, Ignatov V (1999) Biosynthesis of indole3-acetic acid in *Azospirillum brasilense*. Insights from quantum chemistry. Eur J Biochem 259:572–576

Zehnder G, Kloepper J, Yao C, Wei G (1997a) Induction of systemic resistance in cucumber against cucumber beetles by plant growth-promoting rhizobacteria. J Econ Entomol 90:391–396

Zehnder G, Kloepper J, Tuzun S, Yao C, Wei G, Chambliss O, Shelby R (1997b) Insect feeding on cucumber mediated by rhizobacteria-induced plant resistance. Entomol Exp Appl 83:81–85

Zhang BG, Li GT, Shen TS, Wang JK, Sun Z (2000) Changes in microbial biomass C, N, and P and enzyme activities in soil incubated with the earthworms *Metaphire guillelmi* or *Eisenia foetida*. Soil Biol Biochem 32:2055–2062

10 An Insight into Mycorrhiza Involved in Building Soil and Plant Health

M. Ranganathswamy, Gajanan L. Kadam, and Yogeshvari K. Jhala

Abstract

Symbiotic association between fungi and root are known as 'Mycorrhiza', plays a key role in growth of terrestrial plants. Interaction of Mycorrhiza with plants, fungi and environment is obligatory and somewhat complex. Mycorrhiza fungi offer substantial benefits to associated plants like increase in mineral nutrient uptake, protection against soil borne pathogens, increased resistance against abiotic stresses like drought and presence of toxic matters present in soil. They play an important role in sustaining soil health through soil aggregation, improving soil structure and thereby preventing soil erosion. Established fact about plant-mycorhiza association is growth promotion of cereal, fruits and vegetables. The communal request to decrease ecological harms related to unwarranted use of pesticide and growing end users' demands for organic food necessitates integration of microorganisms, such as arbuscular mycorrhizal (AM) fungi in agricultural system.

Keywords

Mycorrhizae · Soil aggregation · Soil health · Biocontrol · Plant health

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10.1 Introduction

The word “mycorrhiza” was invented by Albert Bernhard Frank (1885) to define symbiotic relationship of plant roots and fungi. Mycorrhiza exactly represents “fungus root”. In mycorrhizal relationship, plant roots are colonized by belowground mycelium devoid of any harmful effects to plant. Mycorrhiza represents outcomes of mutualistic association between roots of higher plants and some fungi. However the word “mycorrhiza” was defined in 1885, fossil indication (Remy et al. 1994) and DNA sequence analysis (Simon et al. 1993) advocate that this mutualistic relationship was established 400–460 million years before. Mycorrhiza fungi is in omnipresent in soil and distributed all over the world and establish symbiotic association with roots of majority of terrestrial plants (Willis et al. 2013).

In usual ecologies, it is surprising if a plant roots are not colonized by mycorrhiza. Hence, it could be assumed that mycorrhizal relationship is very usual or nearly widespread phenomena within plant kingdom (Bhagyaraj 2011). However there are diverse types of mycorrhiza, ectomycorrhizae and arbuscular mycorrhizae are generally found abundantly in agricultural soils and found to colonize 75–80% of plant species majorly agricultural, horticultural and hardwood crop species and involved in symbiotic interactions which can benefit both plant and fungi. The fungi colonize root cortical cells by forming haustoria-like structure called arbuscule which aids in interchange of metabolites amongst fungus and host cytoplasm. Hyphal network of mycorrhiza flourish into soil and assist plants in obtaining mineral nutrients and water from soil as well as improve soil structure (Javaid 2009; Rillig and Mummey 2006). Mycorrhizae fungi demonstrated to be a vital part of nutrient cycling in ecosystems (Shokri and Maadi 2009; Yaseen et al. 2012). Several scientists have noticed increase in growth and production of various field crops by root colonization of mycorrhizal fungi (Cavagnaro et al. 2006). Mycorrhizae improve accessibility and supply of phosphorous which is considered to be slowly diffusing ions (Sharda and Koide 2010). Besides their major function in increasing P acquirement, mycorrhizae fungi similarly helps in improving availability of other macro- and micro-nutrients such as N, K, Mg, Cu and Zn, especially in soils where they are present in less soluble forms (Meding and Zasoski 2008).

10.2 Mycorhizosphere

Soil zone surrounding the toots of plant known as rhizosphere is considered to be critical for plant life. Rhizosphere contains abundance of microorganisms and considered to be highly active soil zone due to higher microbial activities. Generally bacteria, algae, fungi, protozoa and actinomycetes colonizes plant roots among which fungi signify a substantial share of soil rhizospheric microorganism and improve plant growth. Symbiotic relationship between fungi and plant roots (mycorrhizae) expands root surface area which in turn facilitates plant to uptake water and nutrients more proficiently from huge soil volume. In addition to improving water and nutrient availability to plants mycorrhizae also protects plants from variety of abiotic stresses (Miransari 2010). Mycorrhizosphere alters microbial populations by influencing competition for site for colonization and photosynthates, stimulation of protection mechanisms by AM fungi aid in defending plants from soil borne pathogens (Siddiqui and Mahmood 1995).

10.2.1 Types of Mycorrhizal Associations

The most common are:

(i) Ectomycorrhiza.
(ii) Endomycorrhiza.
(iii) Ericoid mycorrhiza.
(iv) Orchidaceous mycorrhiza.

10.2.1.1 Ectomycorrhiza (EM)

Temperate forest tree species belonging to families Pinaceae, Salicaceae, Betulaceae, Fagaceae and Tiliaceae found to be colonized with ectomycorrhiza. Above 4000 fungal species, fitting primarily in classes Basidiomycotina and Ascomycotina are known to form ectomycorrhizae. Ectomycorrhizal colonization is characterized by hyphal colonization between root cortical cells resulting in formation of a netlike structure called the Hartig net. Many ectomycorrhiza forms a sheath or mantle of fungal tissue which entirely shield absorbing root. This sheath differ extensively in thickness, color and texture based on specific plant-fungus combination. Nutrients get transferred between various plants by fungal network. The important ectomycorrhizal genera are genera *Boletus, Suillus, Russula, Hebeloma, Tricholoma, Laccaria, Rhizopogon, Scleroderma, Alpova, Pisolithus*, etc. (Smith and Read 2008). These fungi can be grown in laboratory on appropriate media and utilized for application in forest nurseries.

10.2.1.2 Endomycorrhiza

Endomycorrhiza is common terminology used for defining the mycorrhizal types growing within cortical cells of plants. The vesicular arbuscular mycorrhizae (VAM) which are designated as arbuscular mycorrhizal fungi (AMF) belong to phylum Glomeromycota, The generally occurring genera of AM fungi are *Glomus, Gigaspora, Scutellospora, Acaulospora* and *Entrophospora.* Endomycorrhiza are obligate symbionts and that's why could not be cultivated in artificial media. In the soil, AM fungi forms big thick walled latent spores known as extramatricular chlamydospores enabling them to persist adverse soil environment and grow out under favorable environmental conditions. Hyphae of endomycorrhiza enter cell wall and colonize cellular membrane. Following entry in to plant cell, hyphae produce either balloon like (vesicles) or dichotomously branching invaginations (arbuscules) (Mosse 1981). Vesicles are thin walled structures of different sizes and shapes comprising of oil droplets produced in cortical cell of plant roots and serves as storage organs. Structure of arbuscules greatly increases surface area amongst fungal hyphae and cellular cytoplasm to assist in nutrient exchange between them.

10.2.1.3 Ericoid Mycorrhiza

Ericoid mycorrhiza generally found to be associated with plants of families Ericaceae, Empetraceae and Epacridaceae. Fungal hyphae colonize cortical cells of plants but cannot produce arbuscules. Majority of ericaceous species typically found in nutrient poor, acidic soil where ammonium dominates over nitrate.

10.2.1.4 Orchid Mycorrhiza

Orchids are the plants belonging to Orchidaceae family comprising of approximately 30,000 species. Orchids are unavoidably relying on mycorrhiza fungi. Fungi forming association with orchids includes genera *Thanatephorus, Ceratobasidium, Sebacina* and *Tulasnella* (Krishnamurthy and Senthilkumar 2005).

10.3 Mycorrhizae in Soil Health Management

Soil is not just passive material, but is abode of billions of microbes such as actinomycetes, bacteriophages, protozoa, nematodes and fungi that serves as basis of an well-designed symbiotic ecosystem. Soil health is a backbone to carry plant and animal life. Soil health, similarly provide an idea about soil quality. Soil health can be defined as persistent ability of soil to work as a dynamic active environment that bears plants, animals and human beings. According to this definition soil management for maintaining viability of soil is necessary to sustain forthcoming generations.

Healthy soil is base for gainful, productive and ecologically resilient farming systems. Healthy soil offers numerous roles which maintain plant growth, comprising nutrient cycling, biocontrol of crop pests and regulation of water and air supply. Soil health is required to maintain to get sustainable crop production which is dependent on number of factors, mainly conservation of required physical structures, chemical and biological equilibriums in soil.

Soil ecological features are playing a key role in shaping progress of AM symbiotic association (Peng Wang et al. 2015). Now a day due to the intensive agricultural practices increased the disturbances to our soil systems just beginning from land preparation to harvesting of crop. Due to changes in soil structure with resultant negative influence on chemical and biological properties which enhance plant growth and development. In such ruined soil systems, farmers are forced to add up the things which are removed from soil which has been accomplished by application of supplementary fertilizer (Grierson et al. 1991). Due to the intensive agriculture and soil erosion it is difficult to maintain and regain soil sustainability concern to physical and biological properties. Degraded soils loose stable organism composition (Campbell and Greaves 1990) required to maintain throughput. By understanding mechanism of various soil processes supporting plant growth and control ecological excellence are influenced by farming practices, it is likely to develop strategies of crop and soil management system which improve and sustain soil health over period of time. Plants benefits from mycorrihzal when their fungal partner helps in ameliorate resource limitation and protect plants from pathogens.

10.4 Soil Health Improvement Through Mycorrhiza

10.4.1 Soil Aggregation and Conservation

Structure of soil is commonly reflected as measurement of soil aggregate strength and main feature that controls physicochemical and biological characteristics heading soil dynamics (Bronick and Lal 2005). Soil aggregates are comprised of soil minerals (clay particles, fine sand and silt), plant roots, fungal hyphae, remains, bacteria, free amorphous organic matter and organic matter intensely linked to clay coatings (Chenu et al. 2000; Six et al. 2001). Soil aggregates are significant for retaining soil porosity, water filtration, plant and microbial growth, improving strength against wind and water erosion (Rillig et al. 2007; Six et al. 2001). Current agricultural operations gave new burdens on plant mycorrhizal symbiosis. Tillage operations physically disturb soil aggregates and AM hyphal complexes. This act depreciates soil structure, declines fertility and nutrient cycling capacity (Nichols and Wright 2004).

Miller and Jastrow (1992) recommended effect of AM fungi on aggregation can be described as three distinct but simultaneous processes: (1) development of hyphae into soil matrix creating the thin structure that physically entangles primary soil particles, (2) roots and hyphae creating circumstances that enabling microaggregate formation in soil and (3) roots and hyphae entangle resulting in to binding of microaggregates and small macroaggregates into bigger aggregates. This theory is supported by Tisdall et al. (1997) who further found evidence that the efficiency of the fungal hyphae is determined by the hyphal length, surface area and their secretion of polysaccharides.

Hyphal network of both mycorrhiza as well as saprophytic fungi, accompanied by fibrous roots, aggregates soil particles and microaggregates into bigger, aggregated entities (Gupta and Germida 1988; Miller and Jastrow 1990). Microbial partners and plant roots of mycorrhizal association synthesize mucigels and polysaccharides that acts as gums and glues which bind and form steady aggregates (Oades 1984). Role of VAM hyphae in development of soil aggregates is thought to be preliminarily because of physical involvement.

Effect of arbuscular mycorrhizal (AM) fungi on stability of aggregate formed in semi arid Indian vertisol was examined in pot study wherein *Sorghum bicolor* (L.) was grown as trial plant for 10 weeks. Inoculation of AM fungi in pasteurized soil was compared keeping pasteurized and unpasteurized soils as standards. Research outcomes showed that AM fungi helps in stabilization of soil aggregates in vertisol, as well as influence is notable after only one growing season. Stabilization of soil aggregates in vertisol was related to both AM hyphae and enhanced root growth due to AM fungi (Brigette and Petersen 2000).

10.4.2 Wasteland Reclamation

Presently one fifth of the terrestrial ecosystems are under threat of desertification. Starting point of desertification is visualized by disruption of natural plant communities, but is frequently go together with or lead by loss of vital physical, chemical and biological properties of soil (Skujins and Allen 1986). Soil properties mainly govern soil worth and fertility which in turn supports establishment and production of crops. Soil deprivation restricts its prospective for restoration of natural communities of plants. AMF showed great potential for retrieval of degraded soil and usually utilized for reclamation of wastelands. Application of AM fungi can improve growth and persistence of necessary re-vegetation species. Occupation by AMF can produce advantageous physiological influence on host plant in increasing uptake of soil phosphorus. Nicolson (1967) proposed that plant growth in wastelands could be well improved by adding AMF. AM fungi improve plant's capacity of establishment and deal with stressed circumstances comprising nutrient shortage, drought, and soil disruption (Barea et al. 1997). Fungal mycelia spreads from mycorrhizal roots by forming three dimensional net that connects plant roots and soil surroundings. It forms a resourceful structure for nutrient acquisition and searching in nutrient deprived environments. Mycorrhizae fungi showed improvement in re-vegetation of soils polluted with coal spoils, surrounding strip mines as well as waste areas, road sites and other polluted areas (Jha et al. 1994).

10.4.3 Mitigation of Soil Heavy Metal Stress

Trace elements for instance Cu, Fe, Mn, Ni and Zn are critical for natural growth and development of plants. These elements are needed in several enzymatic and oxidation-reduction reactions, electron transfer and having structural role in nucleic acid metabolism (Gohre and Paszkowski 2006). Whereas some of the metals like Cd, Pb, Hg, and As are not vital for plant functions and even toxic even if present in small quantity within soils. The terrestrial plant roots are in direct connection with soil metal ions. Necessary heavy metals are transported into plant roots through definite uptake systems, on the other hand at high quantities they pass in to cell through common carriers. High amount of heavy metals obstruct vital enzymatic reactions by modification of protein structure or by substituting critical element which ultimately results in to deficiency symptoms. As a result toxicity signs like chlorosis, growth delay, browning of roots can be detected.

Transformation of heavy metals means conversion from one oxidation state to another is the only way out to deal with heavy metals (Garbisu and Alkorta 2001), so remediation of heavy metal polluted soils is tougher. Measures like excavation and land fill, thermal treatment, acid leaching and electro reclamation are conventionally utilized for remediation of heavy metals but practical applicability of these measures are limited due to their high cost, low effectiveness, great damage to soil structure and fertility (Hasan et al. 2013). Microbes present in soil plays significant role in mobilization and immobilization of metal cations, thus altering their accessibility to plants. Amongst soil microbes AMF are very common inhabitant of soil present in nearly all the type of soil environment and climate, playing significant functional role in soil-plant system (Barea et al. 1997) including disturbed soils (McGonigle and Miller 1996).

Phytoremediation potential of plants can be improved by inoculation of mycorrhiza fungi as in improves heavy metal availability and plant's tolerance to heavy metals (Gaur and Adholeya 2004). Ectomycorrhiza forms sheath around the plat roots which collect and immobilize heavy metals and that's how it safeguards trees from high concentration of toxic heavy metals like copper, zinc, iron, manganese, cadmium, nickel, etc. capacity of fungi to detoxify heavy metals also provides an added advantage to plants. Mechanism of phytoremediation adopted by plants for heavy metals detoxification comprise of extracellular heavy metal chelation by root exudates, attachment of heavy metals to rhizodermal cell walls, and avoiding heavy metal uptake. Fungal hyphal network serves as a significant sink for heavy metals due to its large surface area of absorption. Alternate storage site for heavy metals are fungal vesicles. Moreover, AM fungi can improve plant's establishment and growth in spite of high concentration of heavy metals in soil by better nutrition (Taylor and Harrier 2001) and relieving abiotic stress (Auge 2001).

Yang et al. (2017) studied influence of arbuscular mycorrhizal fungi (AMF) on glomalin related soil protein dissemination, aggregate stability and their relations with soil properties at various soil depths in lead and zinc polluted sites. Results showed that AMF played an important part in glomalin related soil protein (GRSP), soil organic matter (SOM) and soil organic carbon (SOC) buildup and successively having effect on aggregate development and particle size dispersal in heavy metal contaminated soils. Study emphasized that establishment of native plant accompanying with AMF might serve as an effective biotechnological strategy to help in retrieval of heavy metal contaminated soils.

10.4.4 Improving Soil Fertility Status

Soil organic matter are having significant role in soil fertility and productivity. Soil organic matter exerts several positive effects on soil properties. Organic matter content will decline as the time progresses, and majority of the soil microbiological processes are occurring on soil organic matter and soil colloids (Whipps 1990). Soil properties such as soil organic matter, alkali-hydrolyzable N, available P, and pH were considerably ($P < 0.05$) positively linked with either total AM occupation or richness of spore and hyphae. Arbuscular mycorrhizal fungi can improve nutrient acquisition and thereby helps plants to thrive under limited nutrient conditions (Clark and Zeto 2000). Majority of the research studies reported enhanced P uptake by mycorrhizae but mycorrhizae also reported to help in uptake of other vital elements (Khanday et al. 2016). It is also documented that symbiotic association between plant and mycorrhiza increase uptake of other nutrients like nitrogen, zinc and potassium (Barea et al. 2002) and enhance symbiotic N-fixation ability. Mycorrhizal association changes quality of root secretion. The enhanced root secretion enhances soil micro floral population participating in organic matter decay and nutrient recycling. Dynamic nature of roots by diverse species of mycorrihzal fungi, and wide range of functional response of plants, present complex challanges for understanding all of the roles that mycorrhiza play in soil fertility (Abbott and Johnson 2017).

10.5 Role of Mycorrhizae in Improving Plant Health

10.5.1 Improved Plant Nutrition

Proper nutrition attributes to host endurance against different abiotic and biotic stresses. Host's sensitivity to infections and resistance to disease can be affected by nutritional status of plant and soil fertility status (Cook and Baker 1982). Plant species are benefited from mycorrhizal association because of greater efficiency in nutrient and water uptake (Thakur and Sharma 2013). Mycorrhizal roots increase nutrient absorption capacity through hyphal proliferation, exploration of larger soil volume, durability of absorbing roots, enhanced usage of lesser available nutrients and enhanced retention of soluble nutrients (Clark and Zeto 2000). Beside phosphorous, AM fungi can improve accessibility of Ca, Cu, Mn, S and Zn (Smith and Gianinazzi-Pearson 1988). Plants colonized with mycorrhiza are usually capable to resist infection and root damage as well as photosynthate scavenging by pathogens (Azcon-Aguilar and Barea 1992; Declerck et al. 2002), as mycorrhizae improve host nutrition and general plant growth.

10.5.1.1 Phosphorus Uptake

Phosphorus is a key plant nutrient necessary in fairly high quantities and acts as an essential element for entire biological activities like energy transmission by development of energy rich phosphate ester bonds and similarly a significant component of macromolecules like nucleotiodes, phospholipids and sugar phosphates. Phosphorus is extremely immovable nutrient as it gets readily absorbed by soil particles and phosphate free zone quickly arises nearby plant roots. Mycorrhizal symbioses contribute significantly to phosphorus uptake (Smith and Read 2008) through its extra radial hyphae (Plenchette et al. 2005). Number of researchers reported interactive effect of AM fungi and phosphate solubilizing microorganisms on plant growth (Dar 2010; Tilak et al. 2010). Dar (2010) reported that longer survival and greater population of phosphate solubilizing bacteria in the rhizosphere of lavender and maize plants when applied on seeds or seedlings in mycorrhiza infected roots as compared to of nonmycorrhizal roots. Simultaneous application similarly resulted in improved plant dry matter and phosphorus availability in soils (Dar 2010). Tilak et al. (2010) also established synergistic relation of AM fungi and phosphate solubilizing bacteria on neem and *Pennisetum* grass and several other hosts. Declerck et al. (2002) reported that *G. proliferum* and a *Glomus* sp. strains, increased plant growth and phosphorous content of banana shoots in the presence and absence of the root rot fungus *Cylindrocladium spathiphylli*. Moreover AM inoculation also decreased root injury by pathogen. Graham and Menge (1982) obtained similar results by inoculation of AM fungi or addition of P that decreased wheat take-all disease incidence caused by *Gaeumannomyces graminis*, and hypothesized that improved phosphorous status of plants results in reduction of root exudates utilized for spore germination and infection by pathogens.

10.5.1.2 Nitrogen Uptake

Nitrogen (N) is vital nutrient for plants as it forms basic unit of synthesis of amino acids, protein and nucleic acids. McFarland et al. (2010) described that above 50% of nitrogen necessity of plants can be satisfied by mycorrhiza association. Moreover, mycorrhizae also increases growth, nodulation and nitrogen fixation in legume-*Rhizobium* symbiosis. Mycorrhiza are reported to increase production of phytoalexins in roots of leguminous plants which are chemically iso-flavanoids which in turn increases *nod* gene expression being a flavone (Suresh and Bagyaraj 2002). Increase colonization of host plants with AM due to application of cell-free extracts of *Rhizobium* was reported by numerous researchers (Azcon-Aguilar and Barea 1992; Rea and Tullio 2005). It was than described due to presence of exo-polysaccharides manufactured by *Rhizobium* that could have increased number of infection sites for AM fungi per unit length of root. Simultaneous application of AM fungi and *Frankia* improved total root and shoot dry weight, number of nodules, weight of nodular tissues, as well as N and P content in *Casuarina* (Vasanthakrishna et al. 1994). Subramanian and Charest (1999) showed that corn plant colonized by mycorrhiza displayed higher activities of nitrate reductase, glutamine synthetase and glutamine synthase enzymes in roots and shoots. Guether et al. (2009) discovered that ammonium transporter is activated in mycorrhiza colonized plants which in turn provide assistance in transfer of nitrogen in plant in same way as for phosphorous.

10.5.2 Alleviate Abiotic Stress

Abiotic stresses predispose the host for its vulnerability to disease infection. Plants associated with mycorrhiza are usually having more competence and improved ability to resist environmental stresses as compared to non-mycorrhizal plants. Under drought condition, mycorrhiza colonized plants display enhanced survival as compared to non-mycorrhizal plants. As hyphal network of mycorrhizae spread out deeper and broader in the soil for getting access to water and thereby plant-mycorrhizal symbiosis improves root's hydraulic conductivity and increase water acquisition (Safir and Nelson 1985). Diverse species of mycorrhiza fungi were found to exhibit varying degree of drought tolerance under conditions of moisture stress (Trappe 1962). Many mycorrhizae own precise characteristics to tolerate high soil temperature, pH, moisture, low fertility, salinity and toxins etc., that provides a host plant with competitive benefit enabling improved plant persistence, growth, nutrition and productivity under stress environments (Trappe 1977).

10.5.3 As a Biocontrol Tool in Managing Plant Diseases

Generally agricultural practices like growing disease resistant cultivars, use of chemicals pesticides, preferring crop rotation and soil fumigation etc. can be used as measures to control soil borne pathogens. There are several issues found to be associated with chemical pesticides including higher cost, environmental and public health threats and pests developing resistance against. To overcome such limitation of chemical pesticides scientists have developed biological pesticides which comprise of manipulation or augmentation of beneficial microorganisms to improve plant defense against pathogens (Grosch et al. 2005). Agriculturally useful microorganisms like antagonistic bacteria (*P. fluorescence*, *B. subtilis*, etc.) and fungi (e.g., AMF, *Trichoderma* etc.) generally utilized for biocontrol of pathogens (Berg et al. 2007). AM fungi and other interactive mechanisms associated with crops can decrease harm produced by phyto-pathogens (Siddiqui et al. 1999; Harrier and Watson 2004). AM fungi could be considered as more appropriate and ecologically adequate substitute tool for management of phyto-pathogens in sustainable agricultural system.

10.5.3.1 Mode of Action of Mycorrhizae Fungi for Plant Disease Management Providing a Physical Barrier

Physical barrier prevents entry and proliferation of pathogens by providing a mechanical boundary. *Pisolithus tinctorius* an ectomycorrhizal fungi provide physical barrier in the form of fungal mantle of various thickness on root surface and thus protect from infection of root pathogenic fungi and nematodes. The thick mantle of *Thelephora terrestris* and *P. tinctorius* have been found to protect the seedling of *Pinus echinata* against *P. cinnamomi* (Marx and Davey 1969).

Competition for Space and Nutrients

Mycorhhizal fungi compete with the soil-borne plant pathogens in rhizosphere and rhizoplane for space and nutrients (Smith 1988; Reid 1990; Nemec 1994). Mycorrhizal association utilize surplus carbohydrates from the root exudates and transform to less soluble sugars like trehelose, mannitol, sorbitol etc. The propagules of infectious fungi like *Pythium, Phytophthora, Rhizoctonia, Sclerotium, Fusarium etc.* require nutrients for germination and these are less available in mycorrhizosphere thus discouraging the propagules germination. Davis and Menge (1980) seen local competition amongst AM fungi and *Phytophthora* and reported decrease in *Phytophthora* infection in AM associated roots as well as nearby AM non-colonized roots.

Production of Antibiotics

Numerous Mycorrhizal fungi found to produce different types of antibiotics exhibiting inhibition to pathogenic organisms and protecting the root systems. Antimicrobial constituents manufactured by extraradical mycelium of AMF species *G. intraradices* decrease conidial germination of *F. oxysporum* f. sp. *chrysanthemi* (Filion et al. 1999). Budi et al. (1999) isolated a *Paenibacillus* sp. strain from the mycorrhizosphere of *Sorghum bicolor* plants applied with *G. mosseae* that showed substantial antagonism against *P. parasitica*.

Resistance Against Plant Pathogens

AM fungi are well-known to improve plant's resistance against phyto-pathogens without unwarranted yield losses. This benefit is actually linked to higher photosynthetic ability (Abdalla and Abdel-Fattah 2000; Heike et al. 2001) and a suspension of senescence initiated by pathogens (Heike et al. 2001). *G. mosseae* inoculation in soybean plants tolerated disease incidence by *M. phaseolina*, *Rhizoctonia solani* and *F. solani* as well as higher plant height, shoot weight and root weight as compared to non-mycorrhizal plants (Zambolin and Schenck 1983). *G. mosseae* inoculated plants showed tolerance against the disease incidence as compared to non-mycorrhizal plants rather than affecting disease incidence by pathogens.

Stimulating Beneficial Microbial Activity in Rhizosphere

Rhizospheric microbial population changes due to alterations in root exudate composition by AMF colonization which results into variation in root membrane permeability (Edwards et al. 1998; Kaye et al. 1984; Meyer and Linderman 1986). Microorganisms in mycorhizosphere may interact positively or negatively. Beneficial organisms includes Manganese oxidizing and reducing bacteria (Nogueira et al. 2007), phosphate solubilizing bacteria (Toro et al. 1997), nitrogen transforming microorganisms and that involved in soil aggregation. Mycorrhiza stimulates microbial action and rivalries in roots and thereby restricting pathogens to get access to roots (Rambelli 1973). Alteration of rhizospheric microbial population can cumulatively assist host plants by producing favorable environments for propagation of pathogen inhibiting microflora as displayed for inhibition of *Phytophthora* and *Pythium* spp. in eucalyptus seedlings by Malajczuk and McComb (1979). Unfavorable environmental conditions created by AMF inoculation lead to qualitative modifications in mycorrhizosphere that prohibited *P. cinnamoni* sporangial generation in tomato plants (Meyer and Linderman 1986). Secilia and Bagyaraj (1987) reported that plant root colonization by VAM enables roots to harbor more antagonistic actinomycetes effective against root pathogen and also plays substitutable part of root nutrient absorption by pathogen damaged root system.

Enhances Defense Mechanism by Production of Phenolic and Related Compounds

Plant cells are having capacity to expand inhibitory constituents during their metabolic reaction against pathogenic outbreak, which are considered to be important in imparting resistance in the plant tissues. Symbiotic associations have been found to enhance the concentration of these inhibitors many times greater than non-symbiotic roots. AMF colonization stimulate host roots to synthesize and gather enough quantity of terpenes, phenols etc. which provide resistance to host tissue against pathogen attack (Krupa et al. 1973; Sampangi 1989; Grandmaison et al. 1993). AMF colonization also reported to increase concentration of total soluble plant phenolics such as isoflavonoids or flavonoids, lignin, coumaric acids, etc. in plant roots (Harrison and Dixon 1993).

An increase in concentration and activity of phenylalanine ammonium-lyase and chalcone isomerase enzymes was reported in the course of initial colonization of plant roots by AMF (Lambais and Mehdy 1993; Volpin et al. 1994). *G. mosseae* colonization in tomato plants showed better resistance to *F. oxysporum* and found to have higher phenylalanine and β-glucosidase activity and total phenol content in plant roots (Dehne and Schoenbeck 1979). Strobel and Sinclair (1991) reported that following mycorhizal colonization there was an increase in flavonolic wall infusions in *Laccaria bicolor* that prohibited wound development by pathogen *Fusarium oxysporum* in roots of Douglas fir.

10.5.4 Plant Pathogens Group Controlled by Mycorrhizae

10.5.4.1 Plant Parasitic Nematodes

Plant parasitic nematodes are present in agricultural soils world over, and majority of crops are prone to harm nematodes. Nematode diseases may cause around 50% yield losses which may become more serious when plants are previously infected by other pathogens. Root-knot nematodes have been reported to cause an annual loss up to 29% in tomato, 23% in eggplant 22% in okra, 28% in beans etc., this losses may differ crop to crop and country to country (Sasser 1990). The existence of AMF and plant parasitic nematodes in various crop roots as well as their reliance on host plants for nutrients may result in common relationship of AM fungi, plant parasitic nematodes and host plant. Plant's resistance against nematode infection can be improved by colonization with VAM fungi. VAM inoculation also increase uptake of Ca, Cu, Mn, S and Zn in addition to P. Nematode injured plants often show reduced water conductance via roots and deficits for N, B, Fe, Mg and Zn, especially VAM induced Zn availability demonstrated to contribute resistance to *Melodogyne incognita* in cotton. Kantharaju et al. (2005) showed that VAM fungi colonization supposed to decrease or eradicate harmful influence imposed by root-knot nematodes and significantly decrease nematode growth. Bagyaraj et al. (1979) showed decreased number and size of galls due to root knot nematode infection on tomato plant colonized by AM fungi (*G. fasciculatum*). *G. fasciculatum* harmfully decreased multiplication of *Rotylenchulus reniformis* (Sitaramaiah and Sikora 1982). Siddiqui et al. (2000) reported that coinoculation of *G. mosseae* with *B. japonicum* showed the highest reduction in cyst formation (*Heterodera cajani*) than use of *G. mosseae* alone.

10.5.4.2 Plant Pathogenic Fungi

Diseases produced by phyto-pathogenic fungi persists in soil environment and in remains on soil surface. The soil serves as inoculum for phyto-pathogens. Injury to root and crown tissue is frequently covered in soil; therefore, infections may not be observed up to above ground plant parts will not get severely infected and displaying symptoms like stunting, wilting, chlorosis and death. Plant roots inoculated by AM fungi usually decreases harshness of diseases produced by phyto-pathogens. Reduced harm in mycorrhiza inoculated plants may be because of alterations in root growth and morphology; histopathological modifications in host root; functional and biochemical variations in plant and alterations in host nourishment. Numerous investigators have similarly proved AMF assisted decrease in root rot infection in cereals (Boyetchko and Tewari 1988; Grey et al. 1989; Rempel and Bernier 1990). Stable decline of infection signs has been described for fungal pathogens viz. *Phytophthora, Fusarium, Pythium, Rhizoctonia, Macrophomina, Sclerotium, Verticillium, Aphanomyces* (Rosendahl 1985; Trotta et al. 1996; Rosendahl and Rosendahl 1990; Bhagawati et al. 2000; Guenoune et al. 2001; Torres-Barragan et al. 1996; Liu 1995; Akhtar and Siddiqui 2006). Cordier et al. (1996) revealed that *Phytophthora* growth is decreased by AM fungal colonization and also in neighboring uncolonized areas of AM containing root systems. Pozo et al. (1999) showed that mycorrhizal association considerably defend tomato plants against soil borne pathogen *Phytophthora parasitica* and microscopic as well as biochemical analysis showed that mixture of local and systemic effects are responsible for mycorrhiza mediated defense. AM fungi (*G. etunicatum* BEG168) colonization effect secondary metabolite production and protected cucumber seedlings from wilt caused by *F. oxysporum* f. sp. *cucumerinum* (Hao et al. 2005).

10.5.4.3 Plant Pathogenic Bacteria and Phytoplasma

In addition to nematodes and fungi certain phyto-pathogens like bacteria and phytoplasma too act together with AM fungi on numerous plants. Disease severity affected by these pathogens was usually decreased in mycorrhizal plants. *Glomus mosseae* prohibited infection of soybean plants by *P. syringae* (Shalaby and Hanna 1998), by inhibiting population density of pathogen in soybean rhizosphere. MingQin et al. (2004) observed decrease in disease (*P. solancearum*) in eucalyptus seedlings injected with AM fungi. Combined inoculation of *G. fasciculatum* or *G. mosseae* in mulberry along with 60–90 kg of P per hectare per year decreased occurrence of bacterial blight caused by *P. syringae pv. mori* (Sharma et al.,1995). García-Chapa et al. (2004) reported AM fungus (*G. intraradices*) significantly improved shoot length both in non-Pear Decline and Pear Decline infested pear trees.

10.6 Conclusion

The symbiotic association between mycorrhiza and plant improves moisture and nutrient uptake efficiency of plant species resulting in increased vigor and endurance against biotic/abiotic stresses. It helps in sustaining the soil health through soil aggregation and improving soil physico chemical properties. Mycorrhiza helps in establishment of plant species in degraded soils. It reduces the vulnerability of plant species to pathogens by various protective mechanisms like enhancing nutrient uptake, biochemical defense mechanisms, production of plant growth antibiotics, altering root exudates and microbial inhabitants of mycorrhizosphere. Thus mycorrhizal incorporation can be considered as a key component in building soil and plant health.

References

Abbott LK, Johnson NC (2017) Mycorrhizal mediation of soil: fertility, structure and carbon storage. Elsevier, Amsterdam, pp 93–105

Abdalla ME, Abdel-Fattah GM (2000) Influence of the endomycorrhizal fungus *Glomus mosseae* on the development of peanut pod rot disease in Egypt. Mycorrhiza 10:29–35

Akhtar MS, Siddiqui ZA (2006) Effects of phosphate solubilizing microorganisms on the growth and root-rot disease complex of chickpea. Mikol Fitopatol 40:246–254

Auge RM (2001) Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. Mycorrhiza 11:3–42

Azcon-Aguilar C, Barea JM (1992) Interactions between mycorrhizal fungi and other rhizosphere microorganisms. In: Allen MF (ed) Mycorrhizal functioning: an integrative plant-fungal process. Chapman and Hall, New York, pp 163–198

Bagyaraj DJ, Manjunath A, Reddy DDR (1979) Interaction of vesicular arbuscular mycorrhizas with root knot nematodes in tomato. Plant Soil 51:397–403

Barea JM, Azco'n-Aguilar C, Azcon R (1997) Interactions between mycorrhizal fungi and rhizosphere microorganism within the context of sustainable soil-plant systems. In: Gange AC, Brown VK (eds) Multitrophic interactions in terrestrial systems. Cambridge University Press, Cambridge, pp 65–77

Barea JM, Azcón R, Azcón-Aguilar C (2002) Mycorrhizosphere interactions to improve plant fitness and soil quality. Antonie Van Leeuwenhoek 51:343–351

Berg G, Grosch R, Scherwinsk K (2007) Risk assessment for microbial antagonists: are there effects on non-target organisms? Gesunde Pflanzen 59:107–117

Bhagawati B, Goswami BK, Singh S (2000) Management of disease complex of tomato caused by *Meloidogyne incognita* and *Fusarium oxysporum* f. sp. *lycopersici* through bioagent. Indian J Nematol 30:16–22

Bhagyaraj DJ (2011) Microbial biotechnology for sustainable agriculture, horticulture and forestry. New India Publishing Agency, New Delhi

Boyetchko SM, Tewari JP (1988) The effect of VA mycorrhizal fungi on infection by *Bipolaris sorokiniana* in barley. Can J Plant Pathol 10:361

Brigette NB, Petersen L (2000) Influence of arbuscular mycorrhizal fungi on soil structure and aggregate stability of a vertisol. Plant Soil 218:173–183

Bronick CJ, Lal R (2005) Soil structure and management: a review. Geoderma 124(1–2):3–22

Budi SW, Van Tuinen D, Martinotti G, Gianinazzi S (1999) Isolation from the *sorghum bicolor* mycorrhizosphere of a bacterium compatible with arbuscular mycorrhiza development and antagonistic towards soil borne fungal pathogens. Appl Environ Microbiol 65:5148–5150

Campbell R, Greaves MP (1990) Anatomy and community structure of the rhizosphere. In: Lynch JM (ed) The rhizosphere. Wiley, New York, pp 11–35

Cavagnaro TR, Jackson LE, Six J, Ferris H, Goyal S, Asami D, Scow KM (2006) Arbuscular mycorrhizas, microbial communities, nutrient availability and soil aggregates in organic tomato production. Plant Soil 282(1–2):209–225

Chenu C, Le Bissonnais Y, Arrouays D (2000) Organic matter influence on clay wettability and soil aggregate stability. Soil Sci Soc Am J 64(4):1479–1486

Clark RB, Zeto SK (2000) Mineral acquisition by arbuscular mycorrhizal plants. J Plant Nutr 23:867–902

Cook RJ, Baker KF (1982) The nature and practice of biological control of plant pathogens. APS, St. Paul

Cordier C, Gianinazzi S, Gianinazzi-Pearson V (1996) Colonization patterns of root tissues by Phytophthora nicotianae var. parasitica related to reduced disease in mycorrhizal tomato. Plant Soil 185:223–232

Dar GH (2010) Soil microbiology and biochemistry. New India Publishing Agency, New Delhi

Davis RM, Menge JA (1980) Influence of *Glomus fasciculatus* and soil phosphorus on *Phytophthora* root rot of citrus. Phytopathology 70:447–452

Declerck S, Risede JM, Ruflikiri G, Delvaux B (2002) Effects of arbuscular mycorrhizal fungi on severity of root rot of bananas caused by *Cylindrocladium spathiphylli*. Plant Pathol 51:109–115
Dehne HW, Schoenbeck F (1979) The influence of endotrophic mycorrizae on plant disease. I. Colonization of tomato plants by *Fusarium oxysporum* f. sp. *Lycopersici*. Phytopatholology 95:105–105
Edwards SG, Young JPW, Fitter AH (1998) Interactions between *Pseudomonas fluorescens* biocontrol agents and *Glomus mosseae*, an arbuscular mycorrhizal fungus, within the rhizosphere. FEMS-Microbiol Lett 166:297–303
Filion M, Arnaud M, Fortin JA (1999) Direct interaction between the arbuscular mycorrhizal fungus *Glomus intraradices* and different rhizosphere microorganisms. New Phytol 141:525–533
Frank AB (1885) Uber di auf werzelsymbiose beruhende Ernahrung gewisser Baume durch unterirdischeplize. Ber Dtsch Bot Ges 3:128–145
Garbisu C, Alkorta I (2001) Phytoextraction. A cost-effective plant-based technology for the removal of metals from the environment. Bioresour Technol 77(3):229
García-Chapa M, Batlle A, Lavina A, Camprubi A, Estaun V, Calvet C (2004) Tolerance increase to pear decline phytoplasma in mycorrhizal OHF-333 pear root stock. In: Llacer G (ed) XIX international symposium on virus and virus like diseases of temperate fruit crops-fruit tree diseases, Valencia, Spain
Gaur A, Adholeya A (2004) Prospects of arbuscular mycorrhizal fungi in phytoremediation of heavy metal contaminated soils. Curr Sci 86:528–534
Gohre V, Paszkowski U (2006) Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. Planta 223(6):1115–1122
Graham JH, Menge JA (1982) Influence of vesicular-arbuscular mycorrhizae and soil phosphorus on take-all disease of wheat. Phytopathology 72:95–98
Grandmaison J, Olah GM, Van Calsteren MR, Furlan V (1993) Characterization and localization of plant phenolics likely involved in the pathogen resistance expressed by endomycorrhizal roots. Mycorrhiza 3:155–164
Grey WE, van Leur JAG, Kashour G, El-Naimi M (1989) The interaction of vesicular-arbuscular mycorrhizae and common root rot (*Cochliobolus sativus*) in barley. Rachis 8:18–20
Grierson I, Bull B, Graham R (1991) Soil management and fertilizer strategies. In: White L (ed) Dryland farming. A systems approach. Sydney University Press, South Melbourne, pp 134–145
Grosch R, Lottmann J, Faltin F, Berg G (2005) Use of bacterial antagonists to control diseases caused by *Rhizoctonia solani*. Gesunde Pflanzen 57:199–205
Guenoune D, Galili S, Phillips DA, Volpin H, Chet I, Okon Y, Kapulnik Y (2001) The defense response elicited by the pathogen *Rhizoctonia solani* is suppressed by colonization of the AM fungus *Glomus intraradices*. Plant Sci 160:925–932
Guether M, Balestrini R, Hannah M, He J, Udvardi MK, Bonfante P (2009) Genome-wide reprogramming of regulatory networks, transport, cell wall and membrane biogenesis during arbuscular mycorrhizal symbiosis in *Lotus japonicus*. New Phytol 182:200–212
Gupta VVSR, Germida JJ (1988) Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. Soil Biol Biochem 20:777–786
Hao Z, Christie P, Qin L, Wang C, Li X (2005) Control of Fusarium wilt of cucumber seedlings by inoculation with an arbuscular mycorrhizal fungus. J Plant Nutr 28:1961–1974
Harrier LA, Watson CA (2004) The potential role of arbuscular mycorrhizal (AM) fungi in the bioprotection of plants against soil-borne pathogens in organic and/or other sustainable farming systems. Pest Manag Sci 60:149–157
Harrison MJ, Dixon RA (1993) Isoflavonoid accumulation and expression of defense gene transcripts during the establishment of VA mycorrhizal associations in roots of Medicago truncatula. Mol Plant-Microb Interact 6:643–654
Hasan S, Prakash J, Singh N (2013) Mycorrhizae and phytochelators as remedy in heavy metal contaminated land remediation. Inter Res J Environ Sci 2(1):74–78
Heike G, von Alten H, Poehling HM (2001) Arbuscular mycorrhiza increased the activity of a biotrophic leaf pathogen: is a compensation possible? Mycorrhiza 11:237–243
Javaid A (2009) Arbuscular mycorrhizal mediated nutrition in plants. J Plant Nutr 32:1595–1618

Jha DK, Sharma GD, Mishra RR (1994) Ecology of vesicular-arbuscular mycorrhiza. In: Prasad AB, Bilgrami RS (eds) Microbes and environments. Narendra Publishing House, Delhi, pp 199–208

Kantharaju V, Krishnappa K, Ravichandra NG, Karuna K (2005) Management of root-knot nematode, *Meloidogyne incognita* on tomato by using indigenous isolates of AM fungus, *Glomus fasciculatum*. Indian J Nematol 35:32–36

Kaye JW, Pfleger FL, Stewart EL (1984) Interaction of *Glomus fasciculatum* and *Pythium ultimum* on greenhouse-grown poinsettia. Can J Bot 62:1575–1579

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR et al (eds) Soil science: agricultural and environmental prospective. Springer, Cham, pp 317–332

Krishnamurthy KV, Senthilkumar S (2005) Mycorrhiza: role and applications. Allied Publishers, New Delhi, pp 66–90

Krupa S, Anderson J, Marx DH (1973) Studies on ectomycorrhizae of pine. IV. Volatile organic compounds in mycorrhizal and nonmycorrhizal root systems of *Pinus echinata* mill. Mill Eur J Plant Pathol 3:194–200

Lambais MR, Mehdy MC (1993) Suppression of *endochitinase*, *β-1-3-endoglucanase*, and *chalcone isomerase* expression in bean vesicular-arbuscular mycorrhizal roots under different soil phosphate conditions. Mol Plant Microbe Interact 6:75–83

Liu RJ (1995) Effect of vesicular-arbuscular mycorrhizal fungi on Verticillium wilt of cotton. Mycorrhiza 5:293–297

Malajczuk N, McComb AJ (1979) The microflora of unsuberized roots of Eucalyptus calophylla R. Br. and *Eucalyptus marginata* Donn ex Sm. seedlings grown in soil suppressive and conducive to *Phytophthora cinnamomi* Rands. I. Rhizosphere bacteria, actinomycetes and fungi. Aust J Bot 27:235–254

Marx DH, Davey CB (1969) The influence of ectotropic mycorrhizal fungi on the resistance of pine roots to pathogenic infections III. Resistance of aseptically formed mycorrhizae to infections by *Phytophthora cinnamomi*. Phytopathology 59:549–558

McFarland J, Ruess R, Keilland K, Pregitzer K, Hendrick R, Allen M (2010) Cross-ecosystem comparisons of in situ plant uptake of amino acid-N and NH4+. Ecosystems 13:177–193

McGonigle TP, Miller MH (1996) Development of Fungi below ground in association with plants growing in disturbed and undisturbed soil. Soil Biol Biochem 28:263–269

Meding SM, Zasoski RJ (2008) Hyphal-mediated transfer of nitrate, arsenic, cesium, rubidium, and strontium between arbuscular mycorrhizal forbs and grasses from California oak woodland. Soil Biol Biochem 40:126–134

Meyer JR, Linderman RG (1986) Response of subterranean clover to dual inoculation with vesicular-arbuscular mycorrhizal fungi and a plant growth promoting bacterium *Pseudomonas putida*. Soil Biol Biochem 18:185–190

Miller RM, Jastrow JD (1990) Hierarchy of root and mycorrhizal fungal interactions with soil aggregation. Soil Biol Biochem 22:579–584

Miller RM, Jastrow JD (1992) The role of mycorrhizal fungi in soil conservation. In: Bethlenfalvay CJ, Linderman RG (eds) Mycorrhizae in sustainable agriculture. Crop Science Society and Soil Sci Society of America, Madison, pp 29–44

Mingqin G, Yu C, Fengzhen W (2004) Resistance of the AM fungus *Eucalyptus* seedlings against *Pseudomonas solanacearum*. Forest Res Beijing 17:441–446

Miransari M (2010) Contribution of arbuscular mycorrhizal symbiosis to plant growth under different types of soil stress. Plant Biol 12:563–569

Mosse B (1981) Vesicular arbuscular mycorrhizal research for tropical agriculture. Honolulu University of Hawaii Press, Hawaii

Nemec S (1994) Soil microflora associated with pot cultures of *Glomus intraradix*-infected *Citrus reticulata*. Agric Ecosyst Environ 1:299–306

Nichols KA, Wright SF (2004) Contributions of soil fungi to organic matter in agricultural soils. In: Magdoff F, Weil R (eds) Functions and management of soil organic matter in agro ecosystems. CRC, Washington, DC, pp 179–198

Nicolson TH (1967) Vesicular-arbuscular mycorrhizal: a universal plant symbiosis. Sci Prog (Oxf) 55:561

Nogueira MA, Nehls U, Hampp R, Poralla K, Cardoso EJBN (2007) Mycorrhiza and soil bacteria influence extract-able iron and manganese in soil and uptake by soybean. Plant Soil 298:273–284

Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76:319–337

Peng Wang, Ying Wang, Bo Shu, Jin-Fa Liu, Ren-Xue Xia (2015) Relationships between arbuscular mycorrhizal Symbiosis and soil fertility factors in citrus orchards along an altitudinal gradient. Pedospher Elsevier 25(1):160–168

Plenchette C, Clermont-Dauphin C, Meynard JM, Fortin JA (2005) Managing arbuscular mycorrhizal fungi in cropping systems. Can J Plant Sci 85:31–40

Pozo MJ, Azcon-Aguilar C, Dumas-Gaudot E, Barea JM (1999) B-1,3-glucanase activities in tomato roots inoculated with arbuscular mycorrhizal fungi and/or *Phytophthora parasitica* and their possible involvement in bioprotection. Plant Sci 141:149–157

Rambelli A (1973) The rhizosphere of mycorrhizae. In: Marks GL, Koslowski TT (eds) Ectomycorrhizae. Academic, New York, pp 299–343

Rea E, Tullio M (2005) Microbial biotechnology in agriculture and aquaculture. Science Publishers, Enfield

Reid CPP (1990) Mycorrhizas. In: Lynch JM (ed) The rhizosphere. Wiley, Chichester, pp 281–315

Rempel CB, Bernier CC (1990) *Glomus intraradices* and *Cochliobolus sativus* interactions in wheat grown under two moisture regimes. Can J Plant Pathol 12:338

Remy W, Taylor TN, Hass H, Kerp H (1994) Four hundred-million-year-old vesicular arbuscular mycorrhizae. Proc Natl Acad Sci U S A 91:11841–11843

Rillig MC, Mummey DL (2006) Tansley review – mycorrhizas and soil structure. New Phytol 171:41–53

Rillig MC, Caldwell BA, Wosten HAB, Sollins P (2007) Role of protein in soil carbon and nitrogen storage: controls on persistence. Biogeochemistry 85:25–44

Rosendahl S (1985) Interactions between the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* and *Aphanomyces euteiches* root rot of peas. Phytopathology 114:31–40

Rosendahl CN, Rosendahl S (1990) The role of vesicular arbuscular mycorrhizal fungi in controlling damping-off and growth reduction in cucumber caused by *Pythium ultimum*. Symbiosis 9:363–366

Safir GR, Nelson CE (1985) VA-mycorrhizas plant and fungal water relations. In: Molina R (ed) Proceedings of 6th North American conference on mycorrhiza, Corvallis, p 471

Sampangi RK (1989) Some recent advances in the study of fungal root diseases. Indian Phytopathol 22:1–17

Sasser JN (1990) Economic importance of Meloidogyne in tropical countries. In: Lamberti F, Tayler E (eds) Root-knot news (Meloidogyne sp.) systematics, biology and control. Academic, New York

Secilia J, Bagyaraj DJ (1987) Bacteria and actinomycetes associated with pot cultures of vesicular-arbuscular mycorrhizas. Can J Microbiol 33:1069–1073

Shalaby AM, Hanna MM (1998) Preliminary studies on interactions between VA mycorrhizal fungus *Glomus mosseae*, *Bradyrhizobium japonicum* and *Pseudomonas syringae* in soybean plants. Acta Microbiol Pol 47:385–391

Sharda JN, Koide RT (2010) Exploring the role of root anatomy in P-mediated control of colonization by arbuscular mycorrhizal fungi. Botany 88:165–173

Sharma DD, Govindaiah S, Katiyar RS, Das PK, Janardhan L, Bajpai AK, Choudhry PC, Janardhan L (1995) Effect of VA-mycorrhizal fungi on the incidence of major mulberry diseases. Indian J Seric 34:34–37

Shokri S, Maadi B (2009) Effects of arbuscular mycorrhizal fungus on the mineral nutrition and yield of *Trifolium alexandrinum* plants under salinity stress. J Agron 8:79–83

Siddiqui ZA, Mahmood I (1995) Role of plant symbionts in nematode management: a review. Bioresour Technol 54:217–226

Siddiqui ZA, Mahmood I, Khan MW (1999) VAM fungi as prospective biocontrol agents for plant parasitic nematodes. In: Bagyaraj DJ, Verma A, Khanna KK, Kehri HK (eds) Modern approaches and innovations in soil management. Rastogi, Meerut, pp 47–58

Siddiqui ZA, Mahmood I, Hayat S (2000) Influence of plant symbionts and potassium fertilizer on *Heterodera cajani,* crop growth and yield of pigeon pea under field condition. Indian J Bot Soc 79:109–114

Simon L, Bousquet J, Levesque RC, Lalonde M (1993) Origin and diversification of endomycorrhizal fungi and coincidence with vascular land plants. Nature 363:67–69

Sitaramaiah K, Sikora RA (1982) Effect of mycorrhizal fungus *Glomus fasciculatum* on the host parasite relationship of *Rotylenchulus reniformis* in tomato. Nematologica 28:412–419

Six J, Carpenter A, Van Kessel C, Merck R, Harris D, Horwath WR, Lüscher A (2001) Impact of elevated CO_2 on soil organic matter dynamics as related to changes in aggregate turnover and residue quality. Plant Soil 234:27–36

Skujins J, Allen MF (1986) Use of mycorrhizae for land rehabilitation. MIRCEN J 2:161–176

Smith GS (1988) The role of phosphorus nutrition in interactions of vesicular-arbuscular mycorrhizal fungi with soil borne nematodes and fungi. Phytopathology 78:371–374

Smith SE, Gianinazzi-Pearson V (1988) Physiological interactions between symbionts in vesicular-arbuscular mycorrhizal plants. Ann Rev Plant Physiol Plant Mol Biol 39:221–244

Smith SE, Read DJ (2008) Microbial symbiosis, 3rd edn. Academic, London

Strobel NE, Sinclair WA (1991) Role of flavonolic wall influsions in the resistance induced by Laccaria bicolor to *Fusarium oxysporium* in primary roots of Douglas fir. Phytopathology 81:420–425

Subramanian KS, Charest C (1999) Acquisition of N by external hyphae of an arbuscular mycorrhizal fungus and its impact on physiological responses in maize under drought-stressed and well watered conditions. Mycorrhiza 9:69–75

Suresh CK, Bagyaraj DJ (2002) Arbuscular mycorrhizae: interactions in plants, rhizosphere and soils. Oxford and IBH, New Delhi, pp 7–28

Taylor J, Harrier LA (2001) A comparison of development and mineral nutrition of micropropagated Fragaria × ananassa cv. Elvira (strawberry) when colonized by nine species of arbuscular mycorrhizal fungi. Appl Soil Ecol 18:205–215

Thakur JS, Sharma YP (2013) Effect of ectomycorrhizal inoculation on the growth of apple seedlings. Plant Dis Res 28:35–38

Tilak KVBR, Pal KK, Dey R (2010) Microbes for sustainable agriculture. IK International Publishing House Pvt Ltd, New Delhi

Tisdall JM, Smith SE, Rengasamy P (1997) Aggregation of soil by fungal hyphae. Aus J Soil Res 35(1):55–60

Toro M, Azcón R, Barea JM (1997) Improvement of arbuscular mycorrhiza development by inoculation of soil with phosphate-solubilizing rhizobactera to improve rock phosphate bioavailability (32^P) and nutrient cycling. Appl Envion Micobiol 63:4408–4412

Torres-Barragan A, Zavaleta-Mejia E, Gonzalez-Chavez C, Ferrera-Cerrato R (1996) The use of arbuscular mycorrhizae to control onion white rot (*Sclerotium cepivorum* Berk.) under field conditions. Mycorrhiza 6:253–257

Trappe JM (1962) Fungus association of ectotrophic mycorrhizae. Bot Rev 28:538–606

Trappe JM (1977) Selection of fungi for ectomycorrhizal inoculation in nurseries. Annu Rev Phytopathol 15:203–222

Trotta A, Varese GC, Gnavi E, Fusconi A, Sampo S, Berta G (1996) Interactions between the soil-borne root pathogen *Phytophthora nicotianae* var. *parasitica* and the arbuscular mycorrhizal fungus *Glomus mosseae* in tomato plants. Plant Soil 185:199–209

Vasanthakrishna M, Muthanna MB, Bagyaraj DJ (1994) VA mycorrhizal fungi associated with Casuarina aquisetifolia. Ann For 2:123–126

Volpin H, Elkind Y, Okon Y, Kalpulnik Y (1994) A vesicular arbuscular mycorrhizal fungus (*Glomus intraradices*) induces defence response in alfalfa roots. Plant Physiol 104:683–689

Whipps JM (1990) Carbon economy. In: Lynch JM (ed) The rhizosphere. Wiley, New York, pp 59–99
Willis A, Rodriguesb BF, Harrisa PJC (2013) The ecology of arbuscular mycorrhizal fungi. Crit Rev Plant Sci 32:1–20
Yang Y, He C, Huang L, Ban Y, Tang M (2017) The effects of arbuscular mycorrhizal fungi on glomalin-related soil protein distribution, aggregate stability and their relationships with soil properties at different soil depths in lead-zinc contaminated area. PLoS ONE 12(8):1–19
Yaseen T, Burni T, Hussain F (2012) Effect of arbuscular mycorrhizal inoculation on nutrient uptake, growth and productivity of chickpea (*Cicer arietinum*) varieties. Int J Agron Plant Prod 3:334–345
Zambolin L, Schenck NC (1983) Reduction of the effects of pathogenic root-infecting fungi on soybean by the mycorrhizal fungus, *Glomus mosseae*. Phytopathology 73:1402–1405

11 Mulching: A Sustainable Option to Improve Soil Health

Christopher Ngosong, Justin N. Okolle, and Aaron S. Tening

Abstract

Soil is increasingly recognized as an important non-renewable natural asset that should be properly managed to ensure sustainable development. Hence, this review focuses on the assessment of soil health from an agricultural perspective, with emphasis on mulching as a sustainable strategy to improve soil fertility and productivity of arable systems. Although soil health is essential for sustainable development, sustainability can only be achieved when the system is resource conserving, socio-culturally supportive, commercially competitive, and environmentally friendly. Mulching has demonstrated efficacy to enhance soil health by reducing evaporation, increasing moisture retention, regulating temperature, enhancing nutrient availability and root absorption, suppressing weeds, decreasing salinity, encouraging biological activity, and controlling crop pests and diseases. Organic mulch materials are is commonly used in arable systems to improve soil health, but the use of inorganic plastic mulch has gained global importance in recent decades. Nonetheless, the extensive use of inorganic plastic mulch can cause a series of soil and environmental effects that may affect agricultural productivity and jeopardise sustainable development. Therefore, it is necessary to monitor agricultural soil health in relation to different mulching materials and local environmental conditions, so as to ensure sustainable development. Overall, inorganic mulching materials such as plastic films should be carefully selected in relation to specific needs of farmers and local environmental conditions, while organic mulching is a viable sustainable option to improve soil health and productivity.

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Fertility · Mulch · Organic residues · Plastics · Soil health

11.1 Introduction

Soil is increasingly recognized as an important non-renewable asset that should be properly managed in order to ensure sustainable development. Soil health refers to the ability to function as a vital system that sustains crop productivity within the limits of an ecosystem (Doran and Zeiss 2000; Pompili et al. 2006). Healthy soils are assessed through certain critical interactions of their physical, chemical and biological qualities that maintain fertility and productivity, with the ability to control pests and diseases. Healthy soils improve infiltration and water use efficiency, prevents compaction and erosion, recycles nutrients, and favours natural biological processes. The productivity of arable systems depends on soil health that is reflected by biotic and abiotic indicators such as the soil organic matter, nutrient status, moisture and pH that are largely influenced by management practices (Atkinson et al. 2005; Karlen et al. 2003). Soil health represents critical measures of the degree of sustainability of farming practices, which is a relative judgment that is made according to expectations of soil fitness for agriculture. Hence, farming practices that improve soil organic carbon are essential to enhance soil health and promote sustainable development (Wang et al. 2018).

Farm management practices (e.g. fertilizers, mulching, manure, and pesticides) can affect soil health and influence sustainable development. Mineral and organic fertilizers are important resources that are used by farmers to improve soil health and crop productivity. Synthetic pesticides and botanicals are used to control pests, but long-term reliance on pesticides may lead to pest resistance and environmental pollution (Shelton et al. 2000). Overall, mineral fertilizers and synthetic pesticides exert a multitude of deleterious effects on the environment and are expensive for many resource-poor subsistence farmers in low-income countries. This has necessitated alternative sustainable management strategies to improve soil fertility that are affordable and adapted to the needs of farmers without negative consequences on the environment or humans. Accordingly, integrated soil fertility management (ISFM) has been advocated in recent decades as a sustainable option to improve soil fertility and productivity (Gentile et al. 2009). The ISFM is a holistic approach to soil fertility management using a combination of inherent soil nutrient stocks, locally available inputs (e.g. compost, crop residues, animal or green manure) and mineral fertilizers to improve soil productivity, while preserving the fragile natural resource base. The ISFM embraces a full range of driving forces that affect soil fertility including physical, chemical, biological, social, economic and political factors (Barrios et al. 2006; Vanlauwe and Giller 2006). Moreover, ISFM considers agricultural productivity as essential for sustainable development, since sustainability is only achieved when a system is resource conserving, socio-culturally supportive, commercially competitive, and environmentally friendly.

11.2 Sustainable Soil Health Management

Soil health is the basis for sustainable agricultural development as influenced by farm management practices. Soils comprise approximately 50% solid matter bound together to form aggregates while the rest is air and water. Well-structured soils have stable aggregates that do not easily disperse water, and they have enough pores that promote aeration and water infiltration with easy root penetration. Soil water and nutrient loss is a major problem in agriculture, especially in tropical regions with high temperatures. Non-conservation agricultural practices in areas prone to wind and/or water erosion have further aggravated the situation. In order to find appropriate practices for sustainable soil management, mulching is used often in relation to crop types and climatic conditions (Kader et al. 2017). Ideal soils support biological life that enables natural regeneration of soils and provide adequate supply of essential elements to improve crop performance without toxicity to plants and the environment. In addition, healthy soils enable optimum pH and enhance cation exchange capacity, which ensures nutrient availability for plant use. Moreover, healthy soils support diverse organisms (e.g. fungi, bacteria, nematodes, collembola, and earthworms) with considerable benefits for soil physical, chemical and biological properties. Healthy soil biota facilitates nutrient cycling by decomposing plant and animal residues, which contribute biomass to soil organic matter and form humus. Soil biota converts nutrients that are in organic forms and therefore not available for plant uptake to mineral forms that are available for plant uptake. Soil biota also stabilises soil particle aggregation (structure) that improves soil water-holding capacity and reduces erosion. Moreover, soil biota can improve crop health by out-competing soil-borne pests and pathogens, thereby reducing their potential effects. Symbiotic plant-microbe relationships also enhance soil fertility and plant nutrition (e.g. Mycorrhiza and Rhizobia) while improving crop health (e.g. Beauveria and Trichoderma). Meanwhile, mulching was effective in enabling sustainable soil health, with straw mulch mitigating surface runoff and soil erosion (Linnell et al. 2000; Prosdocimi et al. 2016; Rahma et al. 2017; Lin et al. 2018). Straw mulch favours water infiltration and storage leading to increased soil moisture, and reduced soil salinity and evaporation (Zhao et al. 2014, 2016; Zribi et al. 2015; Jimenez et al. 2017).

11.3 Soil Fertility Management

The soil is an integral component of agricultural systems that serve as a medium for physical, chemical and biological processes that improve soil health and productivity. Although soils can regenerate naturally in undisturbed ecosystems, the continuous cultivation of crops in arable systems leads to soil nutrient depletion and degradation. Ultimately, poor and declining soil fertility resulting from continuous cultivation is a major constraint to crop production and sustainable development (Tening et al. 1995, 2013; Nottidge et al. 2005). Consequently, high input agricultural systems rely on mineral fertilizer amendments to improve soil fertility and plant nutrition (Singh 2000; Saha et al. 2008; Hepperly et al. 2009). Mineral fertilizers are used to improve soil fertility and plant nutrition due to rapid nutrient availability to plants, but their enduring use eventually damages soil physical, chemical and biological properties (Albiach et al. 2000; Thy and Buntha 2005). Meanwhile, simply promoting mineral fertilizers in degraded soils without integrating organic inputs is unsustainable, and will poorly improve or may even worsen soil quality by hastening the loss of soil carbon. Besides deleterious effects on the environment and humans, mineral fertilizers are expensive for resource-poor subsistence farmers in low-income countries (Nziguheba et al. 1998; Laboski and Lamb 2003). Accordingly, low input production systems in Sub-Saharan Africa (SSA) accounts for only 0.1% of global mineral fertilizer production and 1.8% of global mineral fertilizer use, with less than 10 kg ha^{-1} compared to 87 kg ha^{-1} for developed nations (Bationo et al. 2006; FAO 2007). Moreover, poor soil fertility with low fertilizer input accounts for low crop productivity in SSA with huge gaps of over 30% between actual production and attainable potential (Sanchez 2002; Bekunda et al. 2010).

Besides poor and declining soil fertility that constraint agricultural productivity, crop pests and diseases also cause major yield losses that often necessitate the use of synthetic pesticides and fungicides in arable systems. However, reliance on synthetic pesticides and fungicides leads to environmental pollution, pest or disease resistance, and high production costs (Shelton et al. 2000; Susila et al. 2003; Sarfraz and Keddie 2005; Xu et al. 2010). Pesticides are also detrimental to non-target organisms, with potential toxicity on the environment and humans (Fountain et al. 2007; Reinecke and Reinecke 2007; Ghananand et al. 2011; Kumar et al. 2012; Mostafalou and Abdollahi 2013; Fosu-Mensah et al. 2016). This has led to growing concerns and/or the tendency to search for sustainable integrated management approaches that improve soil fertility and crop protection without jeopardising environmental sustainability (Suge et al. 2011). Correspondingly, botanicals are cost-effective alternative farm management practices to control crop pests (Liu et al. 2007; Li et al. 2008; Sayyed et al. 2008; Tanyi et al. 2017). Recently, ISFM has been advocated as cost-effective and sustainable strategy to improve soil health and productivity (Scoones and Toulmin 1998; Vanlauwe and Giller 2006; Sanginga and Woomer 2009; Vanlauwe et al. 2010). ISFM advocates the use of mineral or organic fertilizers, improved germplasm, and legume intercropping (Sanginga and Woomer 2009; Vanlauwe et al. 2010). Within the frame of ISFM, mulching with organic residues and green manures are important resources to improve soil fertility and promote sustainable development. This holistic approach to soil fertility management favours mulching as a cost-effective option to improve arable soil health and enable sustainable development.

11.4 Mulching and Soil Health Management

Mulching uses organic or inorganic materials to improve soil health by facilitating moisture retention, regulating temperature, suppressing weeds, preventing erosion, improving fertility and plant nutrition, and preventing pests and diseases (Groen and Woods 2008; Robichaud et al. 2013; He et al. 2016). Mulching reduces surface water flow and transport capacity by increasing the hydraulic roughness of soil surfaces, and entraps water and soil (Foltz and Wagenbrenner 2010; Montenegro et al. 2013; Shi et al. 2013; Prats et al. 2016). Mulching can be broadly categorized as organic or inorganic depending on the type of materials that are used. However, the particular type of material used for mulching depends on availability and cost, decomposition rate, durability, and the effect on soil properties and functions. Common organic mulch materials with demonstrated efficacy in arable systems include compost, plant and animal residues, and groundcovers. Organic mulch enhances soil health by improving soil fertility and moisture, and optimizing soil temperature with corresponding reduction in surface evaporation and nutrient loss (Montenegro et al. 2013). Common groundcovers or living mulches are usually fast growing nitrogen-fixing plants that grow close to the soil surface under the main crop (e.g. clover, *Pueraria* and *Mucuna*). Such plants form symbiosis with the main crop and contribute significant amounts of nitrogen through biological fixation, and also influence the carbon, nitrogen and phosphorus pools of the microbial biomass (Duda et al. 2003). Straw mulch mediates soil compaction and improve nodulation, nitrogenase activity and yield parameters including seed and protein content of grain legumes (Siczek and Lipiec 2011). Straw mulch reduces accumulation of salts in the rhizosphere with the optimum soil depth depending on the type of mulch material used (Billeaud and Zajicek 1989; Abd El-Mageed et al. 2016). Overall, soil organic matter is considered as ultimate determinant of soil fertility in most soils, which can be improved by organic mulch leading to better soil physical, chemical and biological properties (Albiach et al. 2000; Thy and Buntha 2005).

Alternatively, inorganic materials such as plastic films, rubber, carpet, soil, rocks and gravels can be used for mulching, with soil mulch commonly used in subsistence farming systems in low-income countries with limited financial capital (Ngosong et al. 2016). However, plastic film mulch has gained global importance in recent decades, especially in dry areas that are susceptible to drought (Li et al. 2004; Yu et al. 2018). Nonetheless, discrepancies exist in the performance of organic and inorganic mulches, as organic mulch positively affected root growth and nodulation, while black plastic mulch exhibited negative influences (Dukare et al. 2017). Irrespective of the type of mulch, it is important to understand the specific function of mulch materials in relation to local environments, so as to carefully choose appropriate mulches for use based on the intended objective.

11.4.1 Organic Mulch

Organic mulch materials are usually of plant or animal origin with proven efficacy to enhance soil health (Adekalu et al. 2007; Teame et al. 2017). Organic mulch promotes restoration of degraded soils and improves soil fertility, leading to greater crop productivity (Fang et al. 2007; Kader et al. 2017). Common living mulches include cowpea, bracharia grass and leguminous C. mucunoides, while non-living organic mulches are plant (e.g. rice or wheat straw, and palm) and animal (e.g. poultry, pig, goat, horse, and cow dung) residues (Gholami et al. 2013; Henschke and Politycka 2016; Abrantes et al. 2018; Akhtar et al. 2018). Plant materials have demonstrated efficacy for use as mulch to improve soil health and foster sustainable development (Liang et al. 2002; Berglund et al. 2006; Payam et al. 2013; Adekiya 2018). Plant residues of Tithonia diversifolia (Mexican sunflower) and Mucuna spp. are readily available and cost-effective for improving soil health and crop productivity (Mathews et al. 2003; Ngosong et al. 2016, 2017). Tithonia has high biomass and nutrient contents with 3.5% nitrogen, 0.37% phosphorus and 4.1% potassium (Olabode et al. 2007; Agbede and afolabi 2014). Tithonia also contains some recalcitrant compounds with 6.5% lignin and 1.6% polyphenol (Jama et al. 2000). Mucuna spp. are living mulches with high nitrogen fixing ability and abundant biomass for use in promoting soil health and rejuvenation, as Mucuna biomass contains about 3% nitrogen, 0.2% phosphorus and 1.4% potassium (Mathews and Leong 2000; Mathews et al. 2003; Shaharudin and Yow 2000; Chiu and Bisad 2006). Both Tithonia and Mucuna biomass mulch demonstrated strong potential to promote sustainable soil health by rejuvenating soils and suppressing pests and diseases. Tithonia contains sesquiterpene lactones (tagitinins-terpene) and other antimicrobial substances against pests and diseases (Adoyo et al. 1999; Ojeniyi et al. 2012; Agbede et al. 2014). Similarly, Mucuna comprises stinging hairs, L-DOPA with serotonin and bioactive phytochemicals that may cause irritation and nervous disorders that mitigate crop pests and diseases (Ujowundu et al. 2010; Gitanjali et al. 2016). Mucuna exhibited antimicrobial and fauna properties, influenced the abundance and diversity of soil bacteria and fungi, and suppressed nematodes (Vargas-Ayala et al. 2000; Rayavarapu and Kaladhar 2011; Pujari and Gandhi 2013). Mulching suppresses weed growth, decreases salinity in rhizosphere, reduces water evaporation and enhances soil moisture retention leading to increased water use efficiency of crops (Bu et al. 2002; Chaudhry et al. 2008; Sinkeviciene et al. 2009; Yordanova and Gerasimova 2016). Organic mulch also regulates soil temperature, improves nutrient availability and absorption by roots, and encourages soil biological activity (Liang et al. 2002; Muhammad et al. 2009; Payam et al. 2013). Generally, organic mulch is preferably produced onsite because of the huge bulk that is often required, which makes it impractical and expensive to get sufficient mulch materials externally.

11.4.2 Inorganic Mulch

Inorganic mulches are non-living materials (e.g. plastics, gravels, soils, and carpets) that are used for different agronomic purposes varying from weed control to soil protection (e.g. extreme temperatures and erosion), and to reduce water loss from arable land (Ingman et al. 2015). The total farmland area under plastic mulch has expanded across the globe in recent decades as response to managing water shortage in arable systems that is a major obstacle to sustainable economic development. The effective use of limited water resources is crucial for agricultural development, especially in dry areas with limited soil moisture. Plastic mulch is used as a major water-saving strategy in arable systems across China that is the world's largest plastic film consumer for crop production (Ingman et al. 2015). It increases crop production, improves food quality, reduces surface soil evaporation, prevents fertilizer loss, mitigates drought and flooding or cold and heat, and controls crop pests and diseases (Espi et al. 2006; Bai et al. 2010). Plastic mulch is used on a wide variety of crops to provide protection from unfavorable growing conditions and it represents an important difference between traditional and intensive agricultural systems. Plastic mulch is an important water-saving and temperature regulation strategy that has increased maize and wheat production in dry land areas (Zhou et al. 2009). Plastic mulching increases water use efficiency (Gad El-Moula et al. 2018; Yang et al. 2018), resulting in reduced subsoil water with increased plant growth and transpiration compared to traditional irrigation (Li et al. 1999; Liu et al. 2009). However, the effectiveness of plastic mulch as water-saving strategy depends on the type of surface cover on furrows, climate and soil conditions, and their interactions (Han et al. 2014).

Plastic mulch also face challenges related to differential performance of plastic colours depending on environmental conditions and the purpose for using the coloured plastics (Subrahmaniyan et al. 2008; Ashrafuzzaman et al. 2011; Ocharo et al. 2017). Besides the benefits, potential adverse effects associated with plastic mulch require more studies in different agro-ecological environments to provide greater insight on the influence on soil organisms and their functions. Hence, it is important to ascertain the long-term consequences of plastic mulches on biodiversity and soil health, which may in turn affect productivity and sustainable development. Accordingly, plastic mulch demonstrated idiosyncratic responses to crop protection by suppressing some diseases and enabling the spread of others (Elmer 1991; Bojórquez et al. 2017). Plastic mulch reportedly influenced soil bacteria and fungi, and enhanced the diversity of arthropod and omnivorous insects (Liu et al. 2011; Addison et al. 2013; Muñoz et al. 2015; Farmer et al. 2017). Plastic mulch also reduced watermelon mosaic virus in summer squash, and provided greater protection to some cultivars (Boyhan et al. 2000; Walters 2003). However, plastic mulch either decreased or caused no differences in the diversity and abundance of carabid beetle, springtails, earthworms, parasitic and predatory organisms and the soil food-web structure (Miñarro and Dapena 2003; Tuovinen et al. 2006; Stirling 2008; Addison et al. 2013). The extensive use of plastic mulch in agriculture has also been accompanied by a series of soil, environmental and climate related effects that in turn affect agricultural productivity (Yan et al. 2006, 2014, 2015). Plastic mulch reduced soil invertebrate community structure, decreased microbial activity and species diversity or abundance (Schirmel et al. 2018). Hence, even little shifts in biotic (e.g. food resources) or abiotic (e.g. temperature and moisture) factors induced by plastic mulch can have strong effects on the activities of soil biota. Therefore, plastic mulch can change the long-term quality of arable soils, which may pose viable threats to soil biodiversity and related ecosystem functions in arable fields (Steinmetz et al. 2016). Moreover, plastic additives and residual plastic films can cause soil pollution (Liu et al. 2014; Wang et al. 2016; Vox et al. 2016).

11.5 Impact of Mulching on Crop Pests and Diseases

11.5.1 Living Mulches

According to Matkovic et al. (2015), living mulches are plants grown in association with the main crop to provide various ecological benefits to the main crop including influencing pests, diseases and soil organisms. There are four main attributes of effective living mulches in arable systems, which include the ability to suppress weeds without stressing the crops as a result of quick emergence, fast soil coverage and short height, low insect pest pressure by favouring natural enemies of pests, and contribution to soil nitrogen via N-fixation (Kolota and Sowinska 2013). Burgia et al. (2014) reported higher parasitism of cabbage butterfly (*Pieris brassicae*) larvae in living mulch (88%) than non-living mulch (63%). By contrast, cowpea living mulch effectively suppressed pest populations of pepper (Mochiach et al. 2012). Cover crops also interfere with the emergence of weeds or pests from the soil by impeding dispersal, creating unfavourable soil environment, and the release of allelopathic substances (Brown and Tworkoski 2004).

The attraction of natural enemies of pests is an important ecosystem service provided by living mulches as higher populations of natural enemies were observed in living mulch compared to synthetic and bare-ground treatments for zucchini cultivation (Frank and Liburd 2005). The high population of natural enemies resulted in lower numbers of adult whiteflies and aphids in the living mulch. Cover crops (*Brachiaria decumbens*) increased lower strata species richness, which enhanced abundance of generalist predators and played an important role in regulating the population of banana borer weevil *C. sordidus* (Duyck et al. 2010; Poeydebat et al. 2017). Cover crops likely provided adequate resources to support insect herbivore community that served as alternative preys for generalist predators. However, the use of legume intercrops (*Canavalia ensiformis, Mucuna pruriens, Tephrosia vogelii*) did not affect weevil population and had no benefit for nematode control (McIntyre et al. 2001). In addition, root necrosis was higher in *T. vogelii* intercrop than monocrop, while the legumes did not affect yields. Cover crops such as hairy vetch, Australian winter pea, rye and crimson clover have been used to manage fruit rot diseases in organic tomato production (Nyochembeng et al. 2014).

11.5.2 Non-living Organic Mulches

Non-living mulches are usually made up of non-living plant residues that are biodegradable (e.g. straws, saw dust, wood ash, paper, wood chips, tree backs, and composted animal residues). Such mulches are commonly used in cropping systems because they are available and cheap, relatively easy to acquire and apply on crops. Unlike living mulch that may compete for resources (e.g. light, moisture and nutrients) with main crops, non-living mulch only encourage the diversity of rhizosphere beneficial biota (e.g. bacteria, fungi, earthworms and predators) and provides nutrients that enhance soil fertility and crop performance (Kolota and Sowinska 2013).

Mochiach et al. (2012) reported that straw mulch provided better refuge for natural enemies of pepper pests and enhanced plant performance. However, straw mulch did not increase ground predatory fauna, although onion thrips were significantly higher without compromising the overall onion yield (Larentzaki et al. 2008). Mutetwa and Mtaita (2014) demonstrated that wheat straw mulch suppressed aphids and whiteflies in cucumber production systems but not thrips. According to Gill et al. (2011), different mulches (e.g. cowpea, sunn hemp, pine bark nuggets and sorghum-Sudan grass) affected a wide range of phytophagous insects such as aphids, thrips and whiteflies as well as predatory insects such as beetles and ants.

Non-living organic mulches suppressed weed infestation and altered the composition of weed flora (Petrikovszki et al. 2016). Oroka and Omovbude (2016) reported that mulching with Pennisetum purpureum and Calopogonium mucunoides reduced weed infestation while favouring okra growth and yield. Gill et al. (2011) found that cowpea mulch decomposed quickly and allowed weed emergence that enabled increase in the population of plant-feeding insects. This increase also attracted many predators or natural enemies of crop pests. Cowpea mulch had higher weed coverage, increased phytophagous insects (grasshoppers, sap feeders, and crickets) and higher population of ants and spiders, while beetles and flies showed minimal response (Gill and Goyal 2014). Therefore such mulching is an effective way to provide shelter for predatory insects that play important roles in biological control of insect pests. Paper mulch also controlled weed growth in the cultivation of cucumber (Tapani et al. 2015). Maple leaf mulch suppressed weeds and pests leading to increased tomato yield (Petrikovszki et al. 2016). Maple leaf mulch also reduced tomato root galls induced by *Meloidogyne incognita* that was linked to physical or biological changes, since this gall-forming nematode is thermophilic and affected by increased soil temperature caused by the mulch (Petrikovszki et al. 2016).

In apple orchards, compost mulch (mixture of turkey dung, chicken dung and hard wood chips) was beneficial for managing weeds, fungal diseases and insect pests (Brown and Tworkoski 2004). Plots amended with compost had higher predators with subsequent decrease in the number of herbivorous insects. For banana orchards, Oliveira and Souza (2003) reported that mulching suppressed weeds without affecting the incidence of *C. sordidus* (major biotic constraint on bananas) compared to non-mulched plots. Similarly, grass mulch mixture of *Panicum maximum, Imperata cylindrical and Bracharia* spp. had no effect on banana weevils (Tinzaara et al. 2008). Furthermore, *C. sordidus* was more active and moved longer distances in mulched than non-mulched areas (Gold et al. 1999). Overall, the effectiveness of organic mulch depends on the biochemical constituents of the mulch material (Oroka and Omovbude 2016).

11.5.3 Inorganic Mulch

Plastic mulch materials are widely used as inorganic mulch and different colours of plastic mulches have been evaluated with varying results for pest and disease control that influence crop performance. Muhammed et al. (2017) reported relatively lower armyworms, weevils, diamondback moth, yellow wasps, and ants on black plastic mulch for cabbage. Reflective mulch in combination with imidacloprid and yellow trap significantly reduced aphids and mosaic virus disease incidence (Spehia et al. 2017). White plastic mulch was more attractive to thrips infesting tomato with the lowest numbers found on aluminium mulch, least aphid population occurred on aluminium and yellow plastic mulches, while the highest aphids occurred on blue plastic mulch (Brown and Brown 1992). Low crop yields were reported despite the low number of whiteflies under yellow plastic mulch (Csizinszky et al. 1995). Fewer thrips, aphids, cucumber moths and whiteflies were found on cucumber plants with silver-grey plastic mulch while yellow mulch attracted more aphids and whiteflies (Mutetwa and Mtaita 2014). Generally, metalized mulches have insect-repellent characteristics, which explain why silver-grey mulch had fewer pests. For watermelon cultivation, the number of winged aphids was lower under clear and black plastic mulches (Ban et al. 2009). This is likely due to the quality and quantity of light reflected from mulch surfaces back to the leaves, which affects not only crop growth and development but also the behaviour of insect pests that visit the plants.

Disease suppression also varies with the colour of plastic mulch, as the reflective polyethylene mulch did not suppress tomato diseases (Nyochembeng et al. 2014). However, polyethylene mulch effectively suppressed Phytophthora infestans on tomato plants as compared to fungicides (Shtienberg et al. 2010). This might be because mulching reduced relative humidity in crop canopy, which may have reduced fungal sporulation. Polyethylene mulch also suppressed cucumber downy mildew, but the effect was less compared to P. infestans (Shtienberg et al. 2010). The reduction of foliar diseases in mulched plots is also associated with reduced leaf wetness or splash dispersal of inoculums. The actual effect and magnitude depends on characteristics of the polyethylene film (e.g. chemical composition, colour, thickness and reflectance), and how covering was performed (e.g. attached to soil or not). Moreover, an increase in vitamin-C occurred in chilli (*Capsicum annum*) fruits cultivated with black plastic mulch (Ashrafuzzaman et al. 2011). Meanwhile, black polyethylene mulch effectively suppressed weed incidence by increasing soil temperature and blocking sunlight from reaching weed seeds below the plastic mulch (Ashrafuzzaman et al. 2011; Nyochembeng et al. 2014; Oroka et al. 2016; Nwosisi and Pokharel 2017).

11.5.4 Mechanisms and Limitations of Mulch Action on Pests and Diseases

Mulching has different mode of action on insect pests including interfering with the visual and olfactory host finding ability. It also induces suicidal attraction to sun-heated mulch especially for inorganic mulch, while organic mulch encourage build-up of natural enemies of pests. For instance, ground predatory beetles prefer high mulch areas while aboveground predators and parasitoids prefer living mulches with rich nectar supply that attract more alternative preys and provide essential refuge. Increasing soil temperature especially under plastic mulch creates unfavourable conditions for most soil pests and pathogens. Mulch might produce certain chemicals that either attract or repel pests/pathogens and/or their natural enemies. Organic mulches enhance soil nutrients leading to vigorous plant growth that can enable it to tolerate pests and diseases. Mulch can also induce early flowering and fruiting and therefore help crops to escape from pest attack. Slow nitrogen release from organic manure induces antixenosis that might reduce pest population and activities. Mulch may also cause low pest population on crops but this might not be associated with increase yield. Overall, the associated benefits of mulching vary considerably with respect to the type of mulch material, crop type, farming season, location, type of pest or pathogen, application method and concentration, and climate variables.

Limitations of mulching for pest and disease management involve the type of mulch, especially plastics that can cause considerable increase in soil temperature, which may result in the death of crops. Living mulches can also increase phytophagous insects that can overwhelm their natural enemies and cause more damage to the crop or they may become secondary pests. Some mulch materials can produce chemicals that will attract insect pests leading to greater crop damage. Moreover, inorganic mulches may be ineffective in nutrient deficient soil because they do not contribute additional nutrients to the soil. Overall, mulching for pest and disease control can be expensive and the mulching materials may not be readily available to farmers, especially in subsistence farming systems in low-income countries.

11.6 Conclusion

The recognition of soil as an important non-renewable natural asset that must be well managed to ensure sustainable development has lead to a plethora of views, paradigms and concepts on sustainable soil management. They include integrated soil fertility management, conservation agriculture, integrated nutrient management, organic agriculture, and integrated natural resource management (Lee 2005; Knowler and Bradshaw 2007). These are basically aimed at boosting soil fertility and productivity, while preserving the fragile natural resource base. However, mulching is an integral part of these views, but organic mulching is constraint by the huge amounts and labour cost required for collection, transportation and application (Meertens 2003; Chianu and Tsujii 2005). Therefore, while promoting the use of high value plant residue mulches, their use should be adapted to local environments and the specific needs of farmers. Although organic mulches are commonly used in agriculture, inorganic mulches are increasingly being used but their full range of environmental effects still need to be ascertained, especially the long-term effect of plastics. Overall, both organic and inorganic mulching effectively improved soil health and productivity, with the benefits usually outweighing associated costs (Ngosong et al. 2015; Yu et al. 2018). Nonetheless, considering the dynamic nature of arable soils as influenced by farm management practices, soil health should be monitored regularly in order to ensure sustainable development. Besides standard biochemical tests to measure soil health, the diversity/abundance and function of soil organisms is an important soil quality indicator that should be monitored regularly as they perform essential services that enable sustainability of soil ecosystems (Doran and Zeiss 2000; Barrios 2007; Muñoz et al. 2017).

References

Abrantes JRCB, Prats SA, Keizer JJ, de Lima JLMP (2018) Effectiveness of the application of rice straw mulching strips in reducing runoff and soil loss: laboratory soil flume experiments under simulated rainfall. Soil Tillage Res 180:238–249

Abd El-Mageed TA, Semida WM, Abd El-Wahed MH (2016) Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. Agric Water Manag 173:1–12

Addison P, Baauw AH, Groenewald GA (2013) An initial investigation of the effects of mulch layers on soil-dwelling arthropod assemblages in vineyards. S Afr J Enol Vitic 34:266

Adekalu KO, Olorunfemi IA, Osunbitan JA (2007) Grass mulching effect on infiltration, surface runoff and soil loss of three agricultural soils in Nigeria. Bioresour Technol 98:912–917

Adekiya AO (2018) Legume mulch materials and poultry manure affect soil properties, and growth and fruit yield of tomato. Agric Conspec Sci 83:161–167

Adoyo F, Mukalam JB, Enyola M (1999) Using Tithonia concoctions for termite control in Busia District, Kenya. ILEIA Newsl 13:24–25

Agbede TM, Afolabi LA (2014) Soil fertility improvement potentials of mexican sunflower (Tithonia diversifolia) and Siam weed (Chromolaena odorata) using okra as test crop. Arch Appl Sci Res 6:42–47

Agbede TM, Adekiya AO, Ogeh JS (2014) Response of soil properties and yam yield to Chromolaena odorata (Asteraceae) and Tithonia diversifolia (Asteraceae) mulches. Arch Agron Soil Sci 60:209–224

Akhtar K, Wang W, Ren G, Khan A, Feng Y, Yang G (2018) Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong, China. Soil Tillage Res 182:94–102

Albiach R, Canet R, Pomares F, Ingelmo F (2000) Microbial biomass content and enzymatic activities after the application of organic amendments to a horticultural soil. Bioresour Technol 75:43–48

Ashrafuzzaman A, Halim MA, Ismail MR, Shahidullar SM, Hossain MA (2011) Effect of plastic mulch on growth and yield of chillii (Capsicum annum). Braz Achives Biol Technol 54:321–330

Atkinson A, Black K, Dawson L (2005) Prospects, advantages and limitations of future crop production systems dependent upon the management processes. Ann Appl Biol 146:203–215

Bai L, Hai J, Han Q, Jia Z (2010) Effects of mulching with different kinds of plastic film on growth and water use efficiency of winter wheat in Weibei Highland. Agric Res Arid Areas 28:135–139

Ban D, Zanic K, Dumicic G, Culjak TG, Ban SG (2009) The type of polyethylene mulch impacts vegetative yield and aphid populations in watermelon production. J Food Agric Environ 7:543–550

Barrios E (2007) Soil biota, ecosystem services and land productivity. Ecol Econ 64:269–285

Barrios E, Delve RJ, Bekunda M, Mowo J, Agunda J, Ramisch J, Trejo MT, Thomas RJ (2006) Indicators of soil quality: a South – South development of a methodological guide for linking local and technical knowledge. Geoderma 135:248–259

Bationo A, Hartemink A, Lungu O, Naimi M, Okoth P, Smaling E, Thiombiano L (2006) African soils: their productivity and profitability of fertilizer use. Proceedings of the African Fertilizer Summit, Abuja, 9-13 June 29

Bekunda B, Sanginga N, Woomer PL (2010) Restoring soil fertility in Sub-Sahara Africa. Adv Agron 108:184–236

Berglund R, Svensson B, Gertsson U (2006) Impact of plastic mulch and poultry manure on plant establishment in organic strawberry production. J Plant Nutr 29:103–112

Billeaud LA, Zajicek JM (1989) Influence of mulches on weed control, soil pH, soil nitrogen content, and growth of *Ligustrum japonicum*. J Environ Hortic 7:155–157

Bojórquez AIT, Maza AM, Contreras RLG, Díaz LC, Fidel N-R (2017) Foliar iron and plastic mulch in Capsicum chinense Jacq. infected with tospoviruses. Revista Mexicana de Ciencias Agrícolas 8:369–380

Boyhan GE, Brown JE, Channel-Butcher C, Perdue VK (2000) Evaluation of virus resistant squash and interaction with reflective and nonreflective mulches. HortTechnology 10:574–580

Brown SL, Brown JE (1992) Effect of plastic mulch color and insecticides on thrips population and damage to tomato. Hort Technol 2:208–211

Brown MW, Tworkoski T (2004) Pest management benefits of compost mulch in apple orchards. Agric Ecosyst Environ 103:465–472

Bu YS, Shao HL, Wang JC (2002) Effects of different mulch materials on corn seeding growth and soil nutrients' contents and distributions. J Soil Water Conserv 16:40–42

Chaudhry MR, Malik AA, Sidhu M (2008) Mulching impact on moisture conservation, soil properties and plant growth. Pak J Water Resour 8:1–8

Chianu JN, Tsujii H (2005) Integrated nutrient management in the farming systems of the Savannas of Northern Nigeria: what future? Outlook Agric 34:197–202

Chiu SB, Bisad M (2006) Mucuna bracteata-biomass, litter and nutrient production. The Planter 82:247–254

Csizinszky AA, Schuster DJ, Kring JB (1995) Color mulches influence yield and insect pest populations in tomatoes. J Am Soc Hort Sci 120:778–784

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. Appl Soil Ecol 15:3–11

Duda GP, Guerra JGM, Monteiro MT, De-Polli H, Teixeira MG (2003) Perennial herbaceous legumes as live soil mulches and their effects on C, N and P of the microbial biomass. Sci Agric 60:139–147

Dukare A, Kale S, Kannaujia P, Indore N, Mahawar MK, Singh RK, Gupta RK (2017) Root development and nodulation in Cowpea as affected by application of organic and different types of inorganic/plastic mulches. Int J Curr Microbiol App Sci 6:1728–1738

Duyck PF, Lavigne A, Vinatier F, Achard R, Okolle JN, Tixier P (2010) Addition of a new resource in agroecosystems. Do cover crops alter the trophic positions of generalist predators? Basic Appl Ecol 12:47–55

Elmer WH (1991) Effect of black plastic mulch and nitrogen side-dressing on Verticillium wilt of eggplant. Plant Dis 75(11):1164

Espi E, Salmeron A, Fontecha A, García Y, Real A (2006) Plastic films for agricultural applications. J Plast Film Sheet 22:85–102

Fang S, Xie B, Zhang H (2007) Nitrogen dynamics and mineralization in degraded agricultural soil mulched with fresh grass. Plant Soil 300:269–280

FAO (2007) Policies and actions to stimulate private sector fertilizer marketing in Sub-Saharan Africa. Agricultural management, marketing and finance occasional paper 15

Farmer J, Zhang B, Jin X, Zhang P, Wang J (2017) Long-term effect of plastic film mulching and fertilization on bacterial communities in a brown soil revealed by high through-put sequencing. Arch Agron Soil Sci 63:230–241

Foltz RB, Wagenbrenner NS (2010) An evaluation of three wood shred blends for post fire erosion control using indoor simulated rain events on small plots. Catena 80:86–94

Fosu-Mensah BY, Okoffo ED, Mensah M (2016) Synthetic pyrethroids pesticide residues in soils and drinking water sources from cocoa farms in Ghana. Environ Pollut 5(1):60–72

Fountain MT, Brown VK, Gang AC, Symondson WOC, Murray PJ (2007) The effect of the insecticide chlorpyrifos on spider and collembolan communities. Pedobiologia 51:147–158

Frank DL, Liburd OE (2005) Effects of living and synthetic mulch on the population dynamics of whiteflies and aphids, their associated natural enemies and insect transmitted plant diseases in zucchini. Environ Entomol 34:857–865

Gad El-Moula MMH, Abou-El-Hassan S, Sherif AEA (2018) Mulching and reducing irrigation levels for maximizing water use efficiency of snap bean. Glob J Adv Res 5:178–189

Gentile R, Vanlauwe B, van Kessel C, Six J (2009) Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. Agric Ecosyst Environ 131:308–314
Ghananand T, Prasad CS, Lok N (2011) Effect of insecticides, bio-pesticides and botanicals on the population of natural enemies in brinjal ecosystem. Vegetos-Int J Plant Res 24:40–44
Gholami L, Sadeghi SH, Homaee M (2013) Straw mulching effect on splash erosion, runoff, and sediment yield from eroded plots. Soil Sci Soc Am J 77:268–278
Gill HK, Goyal G (2014) Organic mulches: an innovative pest management strategy. Popular Kheti 2:118–123
Gill HK, McSorley R, Branham M (2011) Effect of organic mulches on soil surface insects and other arthropods. Fla Entomol 94:226–232
Gitanjali D, Harshada K, Sanjay K (2016) Phytochemistry and pharmacological activity of Mucuna pruriens. J Pharm Biol Eval 3:50–59
Gold CS, Karamura EB, Kiggundu A, Bagamba F, Abera AMK (1999) Geographic shifts in highland cooking banana (Musa spp., group AAA-EA) production in Uganda. Int J Sustain Agric World Ecol 6:45–56
Groen AH, Woods SW (2008) Effectiveness of aerial seeding and straw mulch for reducing post-wildfire erosion, north-western Montana, USA. Int J Wildland Fire 17:559–571
Han J, Jia Z, Wu W, Li C, Han Q, Zhang J (2014) Modeling impacts of film mulching on rainfed crop yield in Northern China with DNDC. Field Crop Res 155:202–212
He G, Wang Z, Li F, Dai J, Li Q, Xue C, Cao H, Wang S, Malhi SS (2016) Soil water storage and winter wheat productivity affected by soil surface management and precipitation in dryland of the Loess Plateau. China Agric Water Manag 171:1–9
Henschke M, Politycka B (2016) Application of wood chips for soil mulching in the cultivation of ornamental grasses. Folia Horticulturae 28:187–194
Hepperly P, Lotter D, Ulsh C, Siedel R, Reider C (2009) Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. Compost Sci Util 17:117–1226
Ingman M, Santelmann M, Tilt B (2015) Agricultural water conservation in China: plastic mulch and traditional irrigation. Ecosyst Health Sustain 1:12
Jama B, Palm CA, Buresh RJ, Niang A, Gachengo C, Nziguheba G (2000) Tithonia diversifolia as a green manure for soil fertility improvement in Western Kenya: a review. Agrofor Syst 49:201–221
Jimenez MN, Pinto JR, Ripoll MA, Sanchez-Miranda A, Navarro FB (2017) Impact of straw and rock-fragment mulches on soil moisture and early growth of holm oaks in a semiarid area. Catena 152:198–206
Kader MA, Senge M, Mojid MA, Ito K (2017) Recent advances in mulching materials and methods for modifying soil environment. Soil Tillage Res 168:155–166
Karlen D, Ditzler C, Andrews S (2003) Soil quality: why and how? Geoderma 114:145–156
Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32:25–48
Kolota E, Sowinska KA (2013) Living mulches in vegetable crops production: perspectives and limitations. Acta Sci Pol Hortarum Cultus 12:127–142
Kumar R, Kranthi S, Nitharwal M, Jat SL, Monga D (2012) Influence of pesticides and application methods on pest and predatory arthropods associated with cotton. Phytoparasitica 40:417–424
Laboski CAM, Lamb JA (2003) Changes in soil test phosphorus concentration after application of manure or fertilizer. Soil Sci Soc Am J 67:544–554
Larentzaki E, Plate J, Naut BA, Shetton AM (2008) Impact of straw mulch on populations of onion thrips (Thysanoptera: Thriphidae) in onion. J Econ Entomol 101:1317–1324
Lee DR (2005) Agricultural sustainability and technology adoption: issues and policies for developing countries. Am J Agric Econ 87:1325–1334
Li FM, Guo AH, Wei H (1999) Effects of clear plastic film mulch on yield of spring wheat. Field Crop Res 63:79–86

Li FM, Song QH, Jjemba PK, Shi YC (2004) Dynamics of soil microbial biomass C and soil fertility in cropland mulched with plastic film in a semiarid agro-ecosystem. Soil Biol Biochem Syst 36:1893–1902

Li M, Gao X, Gao Z, Zhao W, Su Z (2008) Insecticidal activity of extracts from forty-eight plants including *Xanthium sibiricum* Patrin. Huanjing Xuebao Jinan 17:33–37

Liang Y, Zhang CE, Guo DW (2002) Mulch types and their benefit in cropland ecosystems on the loess plateau in China. J Plant Nutr 25:945–955

Lin J, Zhu G, Wei J, Jiang F, Wang M, Huang Y (2018) Mulching effects on erosion from steep slopes and sediment particle size distributions of gully colluvial deposits. Catena 160:57–67

Linnell E, Burney JR, Richter G, MacRae AH (2000) Evaluation of compost and straw mulching on soil-loss characteristics in erosion plots of potatoes in Prince Edward Island, Canada. Agric Ecosyst Environ 81:217–222

Liu S, Ji M, Zhao L, Wei S, Wang G, Li X, Li L (2007) Preliminary study on bioactivity of two plant extracts against three kinds of pests. Xiandai Nongyao Shenyang 6:27–29

Liu C, Jin S, Zhou L, Jia Y, Li F, Xiong Y, Li X (2009) Effects of plastic film mulch and tillage on maize productivity and soil parameters. Eur J Agron 31:241–249

Liu Y, Mao L, He X, Cheng G, Ma X, An L, Feng H (2011) Rapid change of AM fungal community in a rain-fed wheat field with short-term plastic film mulching practice. Mycorrhiza 22:31–39

Liu EK, He WQ, Yan CR (2014) 'White revolution' to 'white pollution'-agricultural plastic film mulch in China. Environ Res Lett 9:91001

Mathews J, Leong TT (2000) Performance of two new legume species in oil palm planting. In: Pushparajah E (ed) Proceedings of the international planters conference on plantation tree crops in the new millenium: the way ahead, vol 1. The Incorporated Society of Planters, Kuala Lumpur, pp 325–339

Mathews J, Joseph K, Lakshmanan R, Jose G, Kothandaraman R, Jacob CK (2003) Effect of Bradyrhizobium Inoculation on Mucuna bracteata and Its Impact on the Properties of Soil under Hevea. Proceedings of the 6th International PGPR Workshop, 5-10 October 2003, Calicut, 29–33

Matkovic A, Bozic D, Filipovic V, Radanovic D, Vrbnicanin S, Markovic T (2015) Mulching as a physical weed control method applicable in medicinal plants cultivation. Lekovite Sirovine 25:37–51

McIntyre BD, Gold CS, Kashaija IN, Ssali H, Night G, Bwamiki DP (2001) Effects of legume inter crops on soil-borne pests, biomass, nutrients and soil water in banana. Biol Fertil Soils 34:342–348

Meertens HCC (2003) The prospects for integrated nutrient management for sustainable rainfed lowland rice production in sukumaland, tanzania. Nutr Cycl Agroecosyst 65:163–171

Miñarro M, Dapena E (2003) Effects of groundcover management on ground beetles (Coleoptera: Carabidae) in an apple orchard. Appl Soil Ecol 23:111–117

Mochiach MB, Baidoo PK, Acheampong G (2012) Effects of mulching materials on agronomic characteristics, pests of pepper (Capsicum annum) and their natural enemies population. Agric Biol J N Am 3:253–261

Montenegro AAA, Abrantes JRCB, de Lima JLMP, Singh VP, Santos TEM (2013) Impact of mulching on soil and water dynamics under intermittent simulated rainfall. Catena 109:139–149

Mostafalou S, Abdollahi M (2013) Pesticides and human chronic diseases: evidences, mechanisms, and perspectives. Toxicol Appl Pharmacol 268:157–177

Muhammad AP, Muhammad I, Khuram S, Anwar-UL-Hassan (2009) Effect of mulch on soil physical properties and NPK concentration in Maize (Zea mays) shoots under two tillage system. Int J Agric Biol 11:120–124

Muhammed S, Shoukat RF, Zafar J (2017) Population dynamics of natural enemies and insect pests in different Brassica oleracea (cabbage) growing seasons with different production systems. J Entomol Zool Stud 5:1669–1674

Muñoz K, Schmidt-Heydt M, Stoll D, Diehl D, Ziegler J, Geisen R, Schaumann GE (2015) Effect of plastic mulching on mycotoxin occurrence and mycobiome abundance in soil samples from asparagus crops. Mycotoxin Res 31:191–201

Muñoz K, Buchmann C, Meyer M, Schmidt-Heydt M, Steinmetz Z, Diehl D, Thiele-Bruhn S, Schaumann GE (2017) Physicochemical and microbial soil quality indicators as affected by the agricultural management system in strawberry cultivation using straw or black polyethylene mulching. Appl Soil Ecol 113:36–44

Mutetwa M, Mtaita T (2014) Effect of different mulch colors on cucumber production. J Glob Innov Agric Soc Sci 2:178–184

Ngosong C, Mfombep PM, Njume AC, Tening AS (2015) Integrated soil fertility management: impact of Mucuna and Tithonia biomass on tomato (Lycopersicon esculentum M.) performance in smallholder farming systems. Agric Sci 6:1176–1186

Ngosong C, Mfombep PM, Njume AC, Tening AS (2016) Comparative advantage of Tithonia and Mucuna residues for improving tropical soil fertility and tomato productivity. Int Plant Soil Sci 12:1–13

Ngosong C, Tanyi CB, Njume CA, Mfombep PM, Okolle JN, Njock TE, Nkongho RN, Tening AS (2017) Potential of dual-purpose organic amendment for enhancing tomato (Lycopersicon esculentum M.) performance and mitigating seedling damage by mole cricket (Gryllotalpa africana spp.). IJ Plant Soil Sci 20:1–12

Nottidge DO, Ojeniyi SO, Asawalam DO (2005) Comparative effects of plant residues and NPK fertilizer on soil properties in a humid Ultisol. Niger J Soil Sci 15:9–13

Nwosisi S, Pokharel B (2017) Yield performance of organic sweet potato varieties in various mulches. Horticulture 3:48

Nyochembeng LM, Mankolo RN, Mentreddy SR, Mayalagu G (2014) Cover crop, reflective polyethylene mulch and biofungicide effects on yield and management of diseases in field-grown organic tomato. J Agric Sci 6:265–275

Nziguheba G, Palm CA, Buresh RJ, Smithson PC (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. Plant Soil 247:159–168

Ocharo EN, Korir NK, Gweyi-Onyango J (2017) Green pepper growth and yield response to the integration of mulching materials and row plant spacing. J Agric Crops 3:72–77

Ojeniyi SO, Odedina SA, Agbede TM (2012) Soil productivity improving attributes of Mexican sunflower (Tithonia diversifolia) and Siam weed (Chromolaena odorata). Emirates J Food Agric 24:243–247

Olabode OS, Sola O, Akanbi WB, Adesina GO, Babajide PA (2007) Evaluation of Tithonia diversifolia (Hemsl.) a gray for soil improvement. World J Agric Sci 3:503–507

Oliveira OAP, Souza CM (2003) Effect of mulching on humidity, weeds and Cosmopolites sordidus on bananas (Musa spp) orchard. Rev Bras Fruitic, Jaboticabal Sp 25:345–347

Oroka FO, Omovbude S (2016) Effect of mulching and period of weed interference on the growth, flowering and yield parameters of okra (*Abelmoschus esculentus*). IOSR J Agric Vet Sci 9:52–56

Payam P, Tehranifar A, Nemati H, Llakzian A, Kharrazi M (2013) Effect of different mulching materials on soil properties under semi-arid conditions in Northeastern Iran. Wudpecker J Agric Res 2:80–85

Petrikovszki R, Korosi K, Nagy P, Simon B, Zalai M, Toth F (2016) Effect of leaf litter mulching on pests of tomato. Columella J Agric Environ Sci 3:35–46

Poeydebat C, Tixier P, De Lapeyre De Bellaire L, Carval D (2017) Plant richness enhances banana weevil regulation in a tropical agroecosystem by affecting a multitrophic food web. Biol Control 114:125–132

Pompili L, Mellina AS, Benedetti A (2006) Microbial indicators for evaluating soil quality in differently managed soils. Geophy Res Abstr 8:06991

Prats SA, Wagenbrenner J, Malvar MC, Martins MAS, Keizer JJ (2016) Hydrological implications of post-fire mulching across different spatial scales. Land Degrad Dev 27:1440–1452

Prosdocimi M, Jordan A, Tarolli P, Keesstra S, Novara A, Cerda A (2016) The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci Total Environ 547:323–330

Pujari SA, Gandhi MB (2013) Studies on effects of seed and leaf extracts of Mucuna pruriens on some common bacterial pathogens. J Environ Res Dev 8:50–54

Rahma AE, Wang W, Tang Z, Lei T, Warrington DN, Zhao J (2017) Straw mulch can induce greater soil losses from loess slopes than no mulch under extreme rainfall conditions. Agric For Meteorol 232:141–151

Rayavarapu AK, Kaladhar DSVGK (2011) Evaluation of antimicrobial activity of Mucuna pruriens on plant pathogens. Asian J Biochem Pharm Res 2:593–600

Reinecke SA, Reinecke AJ (2007) The impact of organophosphate pesticides in orchards on earthworms in the Western Cape, South Africa. Ecotoxicol Environ Saf 66:244–251

Robichaud PR, Jordan P, Lewis SA, Ashmun LE, Covert SA, Brown RE (2013) Evaluating the effectiveness of wood shred and agricultural straw mulches as a treatment to reduce post-wildfire hill slope erosion in southern British Columbia. Geomorphology 197:21–33

Saha S, Mina BL, Gopinath KA, Kundu S, Gupta HS (2008) Organic amendments affect biochemical properties of a soil temperate soil of the Indian Himalayas. Nutri Cycl Agroecosyst 80:233–242

Sanchez PA (2002) Soil fertility and hunger in Africa. Science 129:2019–2020

Sanginga N, Woomer PL (2009) Integrated soil fertility management in Africa: principles, practices and developmental process. Tropical Soil Biology and Fertility Institute of the International Center for Tropical Agriculture, Nairobi, 263 pp

Sarfraz M, Keddie BA (2005) Conserving the efficacy of insecticides against *Plutella xylostella* (L.) (Lepidoptera, Plutellidae). J Appl Entomol 129:149–157

Sayyed AH, Saeed S, Noor-Ul-Ane M, Crickmore N (2008) Genetic, biochemical, and physiological characterization of spinosad resistance in *Plutella xylostella* (Lepidoptera: Plutellidae). J Econ Entomol 101:1658–1666

Schirmel J, Albert J, Kurtz MP, Muñoz K (2018) Plasticulture changes soil invertebrate assemblages of strawberry fields and decreases diversity and soil microbial activity. Appl Soil Ecol 124:379–393

Scoones I, Toulmin C (1998) Soil nutrient balances: what use for policy? Agric Ecosyst Environ 71:255–267

Shaharudin B, Yow TK (2000) Establishment of leguminous cover plant (Mucuna bracteata). (Mucuna bracteata). Poster Presentation, The Incorporated Society of Planters, Kuala Lumpur, 17-20 May 2000:317-323

Shelton AM, Sances FV, Hawley J, Tang JD, Boune M, Jungers D, Collins HL, Farias J (2000) Assessment of insecticide resistance after the outbreak of diamondback moth (Lepidoptera: Plutellidae) in California. J Econ Entomol 93:931–936

Shi ZH, Yue BJ, Wang L, Fang NF, Wang D, Wu FZ (2013) Effects of mulch cover rate on interrill erosion processes and the size selectivity of eroded sediment on steep slopes. Soil Sci Soc Am J 77:257–267

Shtienberg D, Elad Y, Bornstein M, Ziv G, Grava A, Cohen S (2010) Polyethylene mulch modifies greenhouse microclimate and reduces infection of Phytophthora infestans in tomato and Pseudoperonospora cubensis in cucumber. Phytopathology 100:97–104

Siczek A, Lipiec J (2011) Soybean nodulation and nitrogen fixation in response to soil compaction and surface straw mulching. Soil Tillage Res 114:50–56

Singh RB (2000) Intensive agriculture during the Green Revolution has brought significant land and water problems relating to soil degradation over exploitation of ground water and soil pollution due to use of high doses of fertilisers and pesticides. Agric Ecosyst Environ 82:97–103

Sinkeviciene A, Jodaugiene D, Pupaliene R, Urboniene M (2009) The influence of organic mulches on soil properties and crop yield. Agron Res 7:485–491

Spehia RS, Phurailatpam S, Sharma S, Devi M, Negi A, Singh S, Sharma JC (2017) Effect of different colours of polyethylene mulch and sticky paper traps on disease incidence and yield of bell pepper under protected cultivation. J Pharmacogn Phytochem 6(3):351–353

Steinmetz Z, Wollmann C, Schaefer M, Buchmann C, David J, Tröger J, Muñoz K, Frör O, Schaumann GE (2016) Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci Total Environ 550:690–705

Stirling GR (2008) The impact of farming systems on soil biology and soilborne diseases: examples from the Australian sugar and vegetable industries – the case for better integration of sugarcane and vegetable production and implications for future research. Australas Plant Pathol 37(1):18

Subrahmaniyan K, Kalaiselvan P, Balasubramanian TN, Zhou W (2008) Soil properties and yield of groundnut associated with herbicides, plant geometry, and plastic mulch. Commun Soil Sci Plant Anal 39:1206–1234

Suge JK, Omunyin ME, Omami EN (2011) Effect of organic and inorganic sources of fertilizer on growth, yield and fruit quality of eggplant (SolanumMelongena L). Arch Appl Sci Res 3:470–479

Susila W, Sumiartha K, Nemoto H, Kawai S (2003) The effect of insecticides on populations of diamondback moth, *Plutella xylostella* (Lepidoptera: Yponomeutidae) and its parasitoid, *Diadegma semiclausum* (Hymenoptera: Ichneumonidae) in cabbage. J Int Soc Southeast Asian Agric Sci 9:132–138

Tanyi CB, Ngosong C, Ntonifor NN (2017) Comparative effects of Piper guineense emulsion and cabbage-tomato intercropping for controlling cabbage pests and improving performance. J of Agric Ecol Res Int 13:1–12

Tapani H, Palonen P, Tamminen A, Ahokas J (2015) Effects of different paper mulches on soil temperature and yield of cucumber (cucumis sativus) in the temperate zone. Agric Food Sci 24:52–58

Teame G, Tsegay A, Abrha B (2017) Effect of organic mulching on soil moisture, yield, and yield contributing components of sesame (Sesamum indicum L.). Int J Agron 2017.:ID 4767509:1–6

Tening AS, Omueti JAI, Tarawali G, Mohamed-Saleem MA (1995) Potassium status of some selected soils under different land-use systems in the subhumid zone of Nigeria. Commun Soil Sci Plant Anal 26(5&6):657–672

Tening AS, Foba-Tendo JN, Yakum-Ntaw SY, Tchuenteu F (2013) Phosphorus fixing capacity of a volcanic soil on the slope of mount Cameroon. Agric Biol J N Am 4:166–174

Thy S, Buntha P (2005) Evaluation of fertilizer of fresh solid manure, composted manure or biodigester effluent for growing Chinese cabbage (*Brassica pekinen*-sis). Livest Res Rural Dev 17:149–154

Tinzaara W, Gold CS, Dicke M, Van Huis A, Ragama A (2008) Effect of mulching on banana weevil movement relative to pheromone traps. Afr Crop Sci J 16(1):59–66

Tuovinen T, Kikas A, Tolonen T, Kivijärvi P (2006) Organic mulches vs. black plastic in organic strawberry: does it make a difference for ground beetles (Col., Carabidae)? J Appl Entomol 130:495–503

Ujowundu CO, Kalu FN, Emejulu AA, Okafor OE, Nkwonta CG, Nwosunjoku EC (2010) Evaluation of the chemical composition of Mucuna utilis leaves used in herbal medicine in Southeastern Nigeria. Afr J Pharm Pharmacol 4:811–816

Vanlauwe B, Giller KE (2006) Popular myths around soil fertility management in sub-Saharan Africa. Agric Ecosyst Environ 116:34–46

Vanlauwe B, Bationo A, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD, Smaling EMA, Woomer PL, Sanginga N (2010) Integrated soil fertility management. Operational definition and consequences for implementation and dissemination. Outlook Agric 39:17–24

Vargas-Ayala R, Rodríguez-Kábana R, Morgan-Jones G, McInroy JA, Kloepper JW (2000) Shifts in soil microflora induced by velvetbean (Mucuna deeringiana) in cropping systems to control root-knot nematodes. Biol Control 17:11–22

Vox G, Loisi RV, Blanco I, Mugnozza GS, Schettini E (2016) Mapping of agriculture plastic waste. Agric Agric Sci Procedia 8:583–591

Walters SA (2003) Suppression of watermelon mosaic virus in summer squash with plastic mulches and rowcovers. HortTechnology 13:352–357

Wang YP, Li XG, Fu T, Wang L, Turner NC, Siddique KHM, Li FM (2016) Multi-site assessment of the effects of plastic-film mulch on the soil organic carbon balance in semiarid areas of China. Agric For Meteorol 228-229:42–51

Wang J, Fu X, Zhao F, Sainju UM (2018) Response of soil carbon fractions and dryland maize yield to mulching. Soil Sci Soc Am J 82:371–381

Xu QC, Xu HL, Qin FF, Tan JY, Liu G, Fujiyama S (2010) Relay-intercropping into tomato decreases cabbage pest incidence. J Food Agric Environ 8:1037–1041

Yan C, Mei X, He W, Zheng S (2006) Present situation of residue pollution of mulching plastic film and controlling measures. Trans Chin Soc Agric Eng 22:269–272

Yan C, Liu E, Shu F, Liu Q, Liu S, He W (2014) Review of agricultural plastic mulching and its residual pollution and prevention measures in China. J Agric Res Environ 31:95–102

Yan C, He W, Liu E, Lin T, Pasquale M, Liu S, Liu Q (2015) Concept and estimation of crop safety period of plastic film mulching. Trans Chin Soc Agric Eng 31:1–4

Yang Y, Zhou X, Yang Y, Bi S, Yang X, Liu DL (2018) Evaluating water-saving efficiency of plastic mulching in Northwest China using remote sensing and SEBAL. Agric Water Manag 209:240–248

Yordanova M, Gerasimova N (2016) Effect of mulching on weed infestation and yield of beetroot (Beta vulgaris ssp. rapaceae atrorubra Krass). Org Agric 6:133–138

Yu Y, Tao H, Yao H, Zhao C (2018) Assessment of the effect of plastic mulching on soil respiration in the arid agricultural region of China under future climate scenarios. Agric For Meteorol 256-257:1–9

Zhao Y, Pang H, Wang J, Huo L, Li Y (2014) Effects of straw mulch and buried straw on soil moisture and salinity in relation to sunflower growth and yield. Field Crop Res 161:16–25

Zhao Y, Li Y, Wang J, Pang H, Li Y (2016) Buried straw layer plus plastic mulching reduces soil salinity and increases sunflower yield in saline soils. Soil Tillage Res 155:363–370

Zhou LM, Li FM, Jin SL, Song Y (2009) How two ridges and the furrow mulched with plastic film affect soil water, soil temperature and yield of maize on the semiarid Loess Plateau of China. Field Crop Res 113:41–47

Zribi W, Aragues R, Medina E, Faci JM (2015) Efficiency of inorganic and organic mulching materials for soil evaporation control. Soil Tillage Res 148:40–45

12 Prospects of Organic Farming as Financial Sustainable Strategy in Modern Agriculture

Ruchi Soni and Sarita K. Yadav

Abstract

Organic farming is an approach of agriculture that involves the cultivation and propagation of crops and livestock without the use of chemical fertilizers, pesticides, genetically modified organisms, antibiotics and growth hormones etc. Organic farming system avoids the use of the chemical synthetic inputs and maximizes the practices of crop rotations, use of animal manures, organic wastes and biological system of micro-macro nutrient mobilization and plant protection in an eco-friendly manner. From last few years, there has been a significant sensitization of the global community on environmental conservation and safe food which relied on agriculture practices based on biological inputs instead of applying synthetic inputs of chemical fertilizers and pesticides. Organic farming has emerged as the only remedy to bring a long lasting sustainability to agriculture. Organic agriculture exhibits the use of traditional agricultural practices that have been known to the farming communities over the decades. As a result this approach not only provides good quality food without chemical constituents but at the same time possess a healthy and cost effective approach to the agriculturists to cultivate an abundance of chemical-free food. The application of organic traditional inputs plays a key role in establishing an economic farming system in the modern agriculture. This chapter will be an attempt to explain the significance of organic farming and application of traditional, indigenous and cost effective approaches in the agriculture so that it will be beneficial to the farmers to perform low-input farming.

Keywords

Organic farming · Organic inputs · Manures · Soil fertility · Sustainability

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12.1 Introduction

Agriculture is the origin for ensuring nutrient and livelihood security globally, hence this sector is becoming resilient to increasing climatic variability. Excess use of chemical fertilizers and pesticides has been proved important tools to facilitate increased crop production in agriculture (Singh et al. 2011). Due to intensive use of chemical inputs including fertilizers, herbicides, and pesticides from the past few decades has led agriculture with various adverse effects (Gattinger et al. 2012). The sustainable agriculture is a recent concept and denotes the maintenance of crop productivity at levels necessary to meet the requirement of increasing population, without deteriorating the environment and the natural resources. Experiencing the destructive and unsafe effects of synthetic input on agriculture, the concept of organic agriculture is gaining thrust.

Organic agriculture is a holistic production management system which endorses and stimulates agro-ecosystem health including biodiversity, biogeochemical cycles, and soil biological and microbial activity. Organic farming system relies on animal manures, crop rotations, crop residues, green manures, legumes, bio-inoculants/bio-fertilizers, safe off-farm organic wastes and aspects of biological pest control management to maintain soil health and crop productivity and limiting use of synthetic inputs and growth regulators in the agriculture to improve soil health and fertility by conserving organic matter level in the soil (Yadav et al. 2013). In order to promote organic farming in agriculturally important and high valuable crops, the use of biological inputs are important in restricting the soil degradation, environmental pollution and also ameliorating the problem of low productivity. In current scenario, the total area in the world under organic certification is 5.71 M ha which includes 26% cultivable area with 1.49 M ha and rest 74% (4.22 M ha) forest and wild area for collection of minor forest produces. The demand for organic produce is rapidly increasing world-wide both in the developed and developing countries with an annual average growth rate of 20–25%.

Excess exploitation of natural resources has forced the human-beings to again adopt the traditional ways of farming. Organic farming emphasizes the application of management practices preferably the use of off-farm inputs, and the indigenous conditions which prefer locally adapted farming systems. This eco-friendly farming system involves the use of economic approaches which helps the farmers to get benefits in agriculture by reducing the cost of expensive synthetic inputs. Keeping in view the above factors, the present chapter emphasizes on prospects of organic farming and its application as cost effective and financial sustainable approach in modern agriculture.

12.2 The Principles of Organic Farming

Organic farming is based on a holistic production management system that depends on promotion and enhancement of agro-ecosystem health along with preserving biodiversity, environmental biological pathways and cycles and biological activities of soil (http://agritech.tnau.ac.in/org_farm/orgfarm_principles.html). The basic principles of organic agriculture are based on.

12.2.1 Health

Organic agriculture is based on sustainability, soil health enhancement, along with human-animal and plant health improvement by implementing maximum use of natural resources.

12.2.2 Ecology

Organic agriculture emphasizes on living ecological organizations and ecological pathways in order to their accomplishment and sustainability.

12.2.3 Harmony with Nature

Organic agriculture maintains relationships and harmony between nature and human being and other creatures of earth that ascertains fairness and justice with respect to the nature and different life opportunities existing on earth.

12.2.4 Care of Natural Resources

Organic agriculture is managed properly in a defensive and conscientious manner to protect current and future generation's health and well-being along with the maintenance of environment.

12.3 Organic Agriculture as Cost Effective Farming System

Organic farming is considered as en easily accessible tool for obtaining sustainable agriculture. It is a rapidly developing agricultural sector world-wide and it works with respect to harmony with nature and implement approaches to the agriculture are 'environmentally friendly' (Roychowdhury et al. 2013). There are various factors which reveal that organic farming is much beneficial than conventional system in modern agriculture (Table 12.1). Nowadays, many farmers are revolving around low input or organic farming as a strategy for economic performance. There are some important aspects of organic agriculture which makes this farming system financial sustainable and economic to the agriculturists:

Table 12.1 Advantages of growing crops through organic farming system than conventional

Factor affecting	Organic farming	Conventional framing
Economy	Low cost for input hence low financial risks	High production cost
	Satisfying yield once soil health is improved	High financial risk
Environment	Increased biodiversity	Pesticides kill beneficial insect-pests
	Eco-balance between beneficial pests-insects	Pollution of soil and water
	No pollution	Resistance of pests
Health	No health risks	Accident with pesticides
	Healthy organic food	Chronic diseases (cancer, infertility, weakness etc.)
Soil	Improved soil health and fertility and crop rotation regularly	Risk of declining soil fertility and poor crop rotation
	Positive relation between buyer and farmer	Lack of buyer's honesty to the farmers
Market	High market value for organic produce	Dependency of farmers of general market rates
	Framers recognized as groups	Individual farmer

(i) It emphasizes the creation of a profitable mode of augmenting life with natural systems.
(ii) It stimulates the production of high quality food in sufficient quantity in an eco-friendly manner.
(iii) It encourages the application of soil beneficial microbes and involvement of plants and animals and organic residues, within biological cycles to sustain agriculture.
(iv) It improves, maintains and enhances the soil fertility.
(v) It maintains and prevents the loss of genetic diversity of plant–animal habitats.
(vi) It establishes proper usage of natural resources.
(vii) It emphasizes a relation between the crop production and animal husbandry.
(viii) It maximizes the use of renewable resources and minimizes the usage of renewable resources leading to reduce environmental pollution.

12.4 Relevance of Conversion of Inorganic Farming to Organic

Conversion to agriculture from inorganic to organic depicts the process of adopting and implementation of natural and eco-friendly ways in the farm to achieve sustainability of the environment. The process of farming may vary from farm to farm and depend on the local circumstances of the area and the tendency of the individual farmer or the farmer community. The conversion process totally depends upon the keen knowledge, concepts, practices and experience of the framer for organic farming. Generally, organic farming system does not depend on particular land conditions, but in case soil condition is not good then it may require great efforts and need more patience to establish a sustainable organic production system. The organic techniques and practices are progressively applied in the farm following a well-organized plan because the alteration from a conventional farming to an organic system requires a transition period. Raddy (2010) stated that during the period of organic agriculture it is an important factor to be carefully analysing the actual condition of the farm in terms of soil, hygiene and level of inorganic fertilizers used and categorize different actions to be taken. The analysis of conditions involves:

- Farm characteristics include crops distribution, type of crops to be sown, size of plots along with plants, animals surrounding incorporated in the farm system.
- Soil analysis comprised of an evaluation testing of the structure of soil, level of nutrients, level of erosion, contamination in soil and organic matter content.
- Climatic condition including frost risks, humidity, rainfall distribution and quantity and temperature variation.
- Organic matter and manure sources and their management.
- Presence of animal and livestock's housing system management.
- Limiting factors may be considered like investments, manpower and market access.

12.5 General Practices Implemented in Organic Conversion

Organic conversion involves implementation of organic practices for soil and weed management instead of following harmful chemical inputs. Implementation of a planned crop rotation like use of weed suppressing green manure and other feed crops in agriculture practices. Further recycling of farm nutrients can be achieved by using animals and crop waste residues to improve farm condition and soil fertility and compost includes one of the best examples of them (Erhart and Hartl 2010). Soil nutrient losses can be avoided by using animal waste and manures. Organic conversion emphasizes the use of healthy seeds and seeds free from pesticide-treatments for sowing. Accurate knowledge and implementation of natural approaches and methods for disease and pest control is required. Knowledge about beneficial insects and regular monitoring of pest-insect population dynamics during crop growth is also an important aspect in organic farming. Some important examples of recommended organic practices intervention include.

12.5.1 Mulching

In this process soil surface is covered with dead plant residues and is proved an easy alternative to manage weeds and defend the soil during annual crop cultivation. This practice can be applied into a wide range of cropping systems (Pupaliene et al.

2015). In this conservation process, the nutrients of bio-waste are recycled naturally and organic wastes are reused as mulches. The refurbishment of soil plant nutrients to the soil, maintenance of soil temperature and moisture, improvement of the beneficial microbial population and ultimately the increase in total organic carbon content are achieved in this process.

12.5.2 Intercrop System for Agriculture Sustainability

The process emphasizes on the cultivation of two different annual crops together, more likely a leguminous crop or a green manure crop with alternating rows with an another cereal or vegetable crop and considered as a common practice in organic agriculture for diversify crop production with maximum land benefit (Barbieri et al. 2017). But during the combination of different crops, competition for light, nutrients and water may be a major limiting factor in this case.

12.5.3 Organic Waste Management (Composting)

It has been found that application of compost in the fields have a major effect on crop growth and yield. Enough plant materials in combination with animal manure are used in this process. To initiate compost production, enough plant material and animal manure will be farmer's major requirement (Chatterjee et al. 2017). In this case, farmers must produce enough plant materials in their farm by sowing fast growing green leguminous plants that result into a lot of biomass and integration and some livestock and animal keeping systems on their farm for manure production. Some experienced persons are needed to instruct farmers and make them practically sound for the preparation of composts. Compost production is totally based on low investments and proper knowledgeable and experienced manpower.

12.5.4 Green Manuring

This is the practice of cultivating a leguminous crop such as calliandra, gliricidia and sesbania etc. to produce a huge biomass and its application in the soil to improve its physical and chemical health. These green leguminous crops also provide nitrogen through nitrogen fixation and act as a favourable source of fodder for livestock. Green manures can be grown in field in combination and rotation with other cereal or vegetable crops. Important aspect is the proper and accurate knowledge about green manure crops species and their utility in organic farming.

12.5.5 Organic Pest Management

It deals with the associations of plants and animals and their management in order to prevent disease outbreak and insect-pest attack in the crop. Initially, bio-control agents/biopesticides were used and applied in fields but nowadays organic pest management is proven as best alternative to achieve and establish an insect-pest balance in the ecology. While, on the other hand the role and choice of resistant crop is always supreme and for that, other prevention methods may include these following factors for organic farming are: selection of appropriate sowing times which will be responsible for less pest outbreaks, improvement of soil health by means of organic practices to resist soil pathogens, crop rotation, applying natural biopesticides/biocontrol agents for biological control of insect-pests, disease and weeds, use of physical barriers for protection against animals, birds, insect-pests and by applying pheromone attractants to trap pests.

12.5.6 Use of Appropriate Seeds for Plantation

Crop production in organic agriculture is achieved by using healthy and disease free seeds as planting material so as to bust up cultivation through improved cultivars. In general, local and indigenous cultivated seeds are preferred because they are better adapted and resilience to the native conditions.

12.5.7 Cultivation of Farm Animal Feed

In this aspect, available foods for the livestock is improved in organic manners such as growing grass in farmer's field, cultivating leguminous fodder crops in combination with other crops or in rotation. As animal feed in an organic process must belong to organic origin and feed sources obtained from the farm are considered as best source of fodder for animals and live stocks.

12.6 Application of Economical Supplements in Organic Farming

A large number of products generally referred as soil and plant organic additives are of non-traditional characteristics and available to be used as eco-friendly alternative in the organic farming system. These products belong to different categories including microbial based biofertilizers and soil inoculants which contain exclusive and beneficial soil micro-organisms like phosphate solubilizers, nitrogen fixers, siderophore producers etc. (Soni et al. 2017), microbial activators that contains particular amount of chemicals or busters for enhancing the population and activity of microflora beneficial for soil health, and soil conditioners that balance and improve soil's physical and chemical conditions that further result in improved plant growth and crop productivity.

12.6.1 Advantages of Bio-fertilizers in Organic Agriculture

Biofertilizers are carrier-based formulation of plant growth promoting bacteria which actively colonizing plant roots and result into increasing the plant growth and improving crop productivity. The *Azospirillum, Azotobacter, Bacillus, Pseudomonas* and *Serratia* genus belong to this beneficial group of bacteria (Glick 2012) It has been reported that they are helpful in improving plant growth and have ability to increase crop yield by 20–25% (Bakonyi et al. 2013). They are low-cost, eco-friendly inputs which reduce the consumption of chemical fertilizer in crop cultivation. They have a role in making easy accessibility and availability of atmospheric nitrogen to the plants by fixing it. The group of soil microbe's phosphate solubilizers solubilize soil phosphorus and increase its uptake to the plants (Soni et al. 2017). They have also been reported to enhance plant growth by excreting plant beneficial hormones such as auxins, gibberellins, cytokines and vitamins etc. (Kloepper 2003). As a result they improve soil fertility and other soil characteristics and sustain the soil health. They also have been found to control and suppress soil borne diseases and thus play suitable role in organic farming. Different types of biofertilizers are described in Table 12.2 (Schutz et al. 2018).

12.6.2 Use of Traditional and Indigenous Solid-Liquid Manures in Organic Farming

They are important in providing all the essential nutrients that are required by plants and helps in maintaining C:N ratio in the soil. Besides that, they have been proven to improve the physico-chemical and biological properties of the soil which further increases its fertility and crop productivity. They play a key role in improving both the structure and texture of the soils, conserve moisture and increase its water holding capacity. They increase in the biological activity by augmenting population of microflora so as to make fix nutrients available to the plants. It's a financial sustainable farming system and farmers will get positive results in a cost effective manner. The following traditional cow product-based organic inputs/organic manures are prepared in a less-expensive manner and are very effective in maintaining the soil health in organic farming (Table 12.3) (Source National Centre of Organic Farming (NCOF), Ghaziabad India:

12.7 An Introduction to Agnihotra and Home Therapy

Agnihotra is basically HOMA fire practices wrought in the ancient Vedic sciences in order to maintain bioenergy, biogenetics, psychotherapy, medication and farming and to balance climatic variation and astronomical communication (Lahoty and Rana 2013). It is a process of purifying the air by means of particularly prepared fire. Since it also works harmony with nature and possesses a direct relation with organic farming practice. Its process involves a small fire in a gold or copper

Table 12.2 Categorization of different microbial inoculants as biofertilizers

Category	Groups	Examples
N2 fixing biofertilizers	Free-living	*Azotobacter, Beijerinkia, Clostridium, Klebsiella, Anabaena, Nostoc,*
	Symbiotic	*Rhizobium, Frankia, Anabaena azollae*
	Associative symbiotic	*Azospirillum*
P solubilizing biofertilizers	Bacteria	*Bacillus megaterium* var. *phosphaticum, Bacillus subtilis Bacillus circulans, Pseudomonas striata, Arthrobacter chlorophenolicus, Bacillus firmus, B. megaterium, B. mucilaginous, Burkholderia caryophylli, Enterobacter asburiae, Microbacterium arborescens, Paenibacillus sp., P. polymixa, Providencia sp., Pseudomonas aeruginosa, P. argentinensis, P. cepacia, P. chlororaphis subsp. aurantiaca, P. diminuta, P. fluorescens, P. fragi, P. jesseni, P. marginalis, P. paleroniana, P. putida, P. striata, P. syringae, P. tolasii, Serratia marcescens, Staphylococcus saprophyticus*
	Fungi	*Aspergillus awamori, Penicillium sp, Penicillium bilaii*
P mobilizing biofertilizers	Arbuscular mycorrhiza	*Glomus sp.,Gigaspora sp.,Acaulospora sp., Scutellospora sp. & Sclerocystis sp.*
	Ectomycorrhiza	*Laccaria sp., Pisolithus sp., Boletus sp., Amanita sp.*
	Ericoid mycorrhizae	*Pezizella ericae*
	Orchid mycorrhiza	*Rhizoctonia solani*
N fixers and P solubilizes	Bacteria	Strains of *Bacillus megaterium*, *B. polymixa*, *Enterobacter* sp., consortia of P solubilizers and N fixers
Biofertilizers for micro-nutrients	Silicate and Zinc solubilizers	*Bacillus* sp.
Arbuscular mycorrhiza fungi	Fungi	*Entrophosphora colombiana, Glomus caledonium, G. clarum, G. etunicatum, G. fasciculatum, G. hoi, G. intraradices* (*new name: Rhizophagus irregularis*), *G. mosseae, Gigaspora rosea*

pyramid using dried cow-dung cakes and adding some rice grains with pure ghee into the fire accurately at the time of sunrise and sunset in addition to two chants. Basically it is adjusted to the biorhythm in consistent to sunrise and sunset. Copper is a good conductor for restrained energies and at morning all the energies are attracted to the pyramid. Agnihotra homa therapy is a holistic approach to heal the atmosphere and soil and can be used concurrence with organic farming system.

One study revealed that growth parameters of rice in terms of germination rate, root-shoot length, fresh weight and dry weight were significantly higher in Agnihotra treatment sacrifice with *mantra* in comparison to the treatments of Agnihotra without chanting mantras and the rice seeds germinated in the normal conditions (Devi et al. 2004). Although a very less literature is available about this strategy and its implementation in organic farming and as such no scientific validations or

Table 12.3 Some commonly used indigenous organic formulations in organic farming

Organic input	Purpose	Ingredients used	Methods of preparations	Mode of application	Reference
Panchagavya	Plant growth and soil enrichment	Cow dung slurry, fresh cow dung, cow urine, cow milk, curd and cow butter oil (4:1:3:2:2:1)	Mix all the ingredients thoroughly and ferment for 7 days with twice stirring per day	Soil and seed treatment	Somasundaram and Amanullah (2007)
Enriched panchagavya	Plant growth and soil enrichment	Fresh cow dung, cow urine, cow milk, curd, cow deshi ghee, sugarcane juice, coconut water (1:3:2:2:1:3:3) enriched with banana paste of 12 fruits	Same as above	Soil and seed treatment	Gopakkali and Sharanappa (2014)
Beejamrut	Plant growth	Cow dung, cow urine, cow milk, lime, water (5:5:1:0.25:100)	Mix all the ingredients and keep it for overnight. Dry in shade before sowing	Seed treatment	Gore and Sreenivasa (2011)
Matka khaad	Plant growth and soil enrichment	Cow dung, cow urine, water and jaggery (1:1:1:0.25)	Mix all the ingredients in a earthen pot and incubate for 10 days at room temperature	Soil and seed treatment	Soni et al. (2017)
Vermiwash	Plant growth and protection	Cow dung 12–15 kg and earthworm 200–300 no	Fill a pitcher with a layer of sand along with a layer of dry biomass and a thick covering of cow dung, adult earthworms were added and hanged under a shady area. Another pitcher filled with water placed over it and another empty pitcher was placed below it to collect the brown colored leachate	Seed treatment and foliar spray	Soni and Sharma (2016)
Sanjivak	Soil enrichment	Cow dung, jaggary, cow urine and water (2:0.005:1:3)	Mix all the ingredients in a drum and ferment for 10 days	Soil treatment	Bhat et al. (2017)
Jeevamrit	Soil enrichment	Cow dung, cow urine, jaggary, gram flour, soil and water (1:1:0.2:0.2:0.1:20)	Mix this solution well with wooden stick and keep this solution for fermentation for 5–7 days	Soil treatment	Gore and Sreenivasa (2011)
Amrutpani	Soil enrichment	Cow dung, honey, cow desi ghee and water (1:0.5:0.25:20)	Mix all the ingredients and preserve for 10 days at room temperature.	Soil treatment	Bhat et al. (2017)

Organic input	Purpose	Ingredients used	Methods of preparations	Mode of application	Reference
Fermented butter milk	Plant protection	Butter milk, cow urine and water (1:1:20)	Ferment the mixture in an earthen pot for 15–21 days	Foliar spray, useful against strong pest repellent	Bhat et al. (2017)
Dashparni extract (Ten plant's extract)	Plant protection	Leaves of neem, Chinese chastetree, pipevine, papaya, guduchi, custard apple, karanja, castor, oleander, rubber bush, green chilly paste, garlic paste, cow dung, cow urine and water (5:2:2:2:2:2:2:2:2:2:2:0.25:3:5:200)	Crush all the ingredients and ferment for 1 month in shade and cover with gunny bag. Shake regularly three times a day and can be stored up to 6 months	Foliar spray, useful against strong pest repellent	Bhat et al. (2017)
Neemastra	Plant protection	Neem leaves, cow urine and cow dung (5:5:2)	Ferment the mixture for 24 h with intermittent stirring, filter squeeze the extract and dilute to 100 l	Foliar spray useful against sucking pests and mealy bugs	Source NCOF, Ghaziabad
Brahmastra	Plant protection	Cow urine, leaves of neem, custard apple, papaya, pomegranate, guava (10:3:2:2:2:2)	Mix the ingredients and boil 5 times at some interval till it becomes half ferment the mixture for 24 h, filter squeeze the extract and dilute to 100 l	Foliar spray, useful against sucking pests, pod/fruit borers.	Source NCOF, Ghaziabad
Agneyastra	Plant protection	Ipomea (besaram) leaves, hot chilli, garlic, neem leaves, cow urine (1:0.5:0.5:5:10)	Boil the suspension 5 times till it becomes half, filter and squeeze the extract. Store in glass or plastic bottles, 2–3 l extract diluted to 100 l	Foliar spray useful against leaf roller, stem/fruit/pod borer	Source NCOF, Ghaziabad

reasoning is mentioned in previous studies. This ancient Vedic farming practice can be used by farmers which capacities in enhancing crop productivity with minimal input costs, well treating the atmosphere, soil, plants and animals and resolve pests and disease problems in the agriculture.

12.8 Significance of Biodynamic Farming in Organic Agriculture

Biodynamic (BD) farming was proposed by Steiner (1924) as one of the oldest organic agricultural farming approaches which is determined for long-term diversified farms which could offer natural, cost-effective and substantial sustainability for mankind. The BD method also focuses on a holistic approach toward agriculture and has become the topic of keen interest of the agriculturists during the past decades. BD preparations including use of animal manures, cow horns, composting, plant material and silica etc. (Turinek et al. 2009) (Table 12.4) contribute toward the fortification of the ecology; conserve biodiversity and ultimately betterment of livelihoods of farmers. Basic principles of biodynamic farming are focused on treating a farm as a single entity or an organism. It should remain as enclosed from their surrounding ecosystems as if possible. The farms are structured around lunar and astrological cycles which are supposed to affect the biological and ecological systems. They are constructed in a way to integrate all the living entities together including plants, livestock and farmers and the soil is treated as the central constituent of all biodynamic farms (https://www.bellamysorganic.com.au/blog/what-is-the-difference-between-biodynamic-and-organic-farming/).

Table 12.4 Details of BD preparations, their major ingredients, mode of application and role in organic agriculture

Name of preparation	Major ingredients	Mode of application	Role in soil health
BD 500	Cow manure	Field spray	Soil biological activity
BD 501	Silica	Field spray	Plant resilience
BD 502	Yarrow flowers (*Achillea millefolium* L.)	Compost preparation	K and S processes
BD503	Chamomile flowers (*Matricaria recutita* L.)	Compost preparation	Ca and K processes
BD 504	Stinging nettle shoots (*Urtica dioica* L.)	Compost preparation	N management
BD505	Oak bark (*Quercus robur* L.)	Compost preparation	Ca processes
BD 506	Dandelion flowers (*Taraxacum officinale* Web.)	Compost preparation	Si management
BD 507	Valerian extract (*Valeriana officinalis* L.)	Field spray, compost preparation	P and warmth process

12.9 Economic Benefits of Organic Farming to Farmers

Many farmers have adopted organic farming as low input agricultural strategy for economic endurance. Several comparisons between organic and conventional farming showed that former one exceeds the next in economic performance. However, organic farming necessitates more intensive and concrete management than conventional farming. A diversified cropping system in organic farms can provide many economic benefits because cultivating different crops in same farm posses' significant protection from sudden price change in single commodity coupled with an improved seasonal distribution of inputs. Organic farmers grow variety of crops on a farm and generally the entire cultivation seem invulnerable to the same pests or seasonal climatic impacts (Fess and Benedito 2018). If there is a total crop failure, organic growers suffer comparatively less economic damage as they invest less in purchasing chemical inputs during conventional approach. Organic farmers suppose to invest fewer funds because they need not to buy chemical inputs like fertilizer, fungicides and pesticides etc. and moreover, the costs and income are equally distributed on diversified organic farms annually.

Some farmers claimed that the field soils have superior tilth and less compaction after using organic inputs. Altered soil structure, along with enhanced ground cover, reduced runoff by about 10–50% and improved infiltration by about 10–25% (Gerhardt 2012). All these factors lead to lessen soil erosion in the fields cultivated organically by at least two-fifths, and sometimes over four-fifths (Cacek 1984). It has been noticed that the crops are generally less susceptible to drought and other natural calamities when organic practices are properly established in the fields because organically cultivated soils absorb significantly more available rainfall, facilitating protection from drought (Cacek 1984). However, the disinclination of organic farmers to apply prophylactic antibiotics reduces the probability of confinement feeding systems. Organic farmers require less irrigation because they use more crop rotations leading to higher soil permeability (Cacek and Linda 1986). It was previously believed that organic farmers' avoidance to use chemical fertilizers may result into depletion of phosphorus, potassium, and other micro-elements, and the deficiency can cause adverse long-term biological and economic impacts (USDA 1980). But latest research revealed that the organic farming is a better approach for the management of soil physico-chemical characteristics because of continues use of manure recycling (Fess and Benedito 2018). However, more studies based on research plots and economic models are required to identify optimum economic performance of organic farms in comparison to conventional farming.

12.10 Scope of Organic Farming in Modern Agriculture

The awareness about the adverse effects due to excessive use of chemicals in agriculture, the people have become more conscious about the food quality and hence increasing the demand in organic products in market. The resilient sustainability for environment coupled with increase in crop yield and the organic farming has emerged as an eco-friendly and long-lasting tool in agriculture. The movement of organic farming started with developed world is gradually followed by the developing countries. For any country, success of organic farming movement only depends upon the growth of its own domestic markets. In organic agriculture, the role of modern, intensive and scientific approaches in agriculture traditional farming is missed off. There is a need to develop a proper and well-defined marketing channel to ensure premium price of the organic-product to boost up the interest of organic farming in the mankind. There are some measures to be recommended to promote organic farming like improvement in the marketing channels, guarantee in regular supply and premium price for the organic products, creation of standards for packaging and branding of organic products, establishment of organizations world-wide to promote organic farming. It will not only compensate the quality and sustainability concerns, but also endow a less-expensive and a profitable livelihood for framers.

12.11 Conclusions

Organic farming emphasizes at defending agricultural agro-ecosystem by promoting the eco-friendly practices in agriculture that facilitates natural soil fertility, conserving the environmental biodiversity and limiting the use of harmful chemical products. It relies on holistic approach for the cultivation of organic crops that integrates various elements including social, environmental, economic, and technological aspects. The crop productivity is reported as significantly improved through organic farming at lower input levels, which can make it more profitable to the farmers. The greater profitability is also due to less labor requirement and to greater market demands for organic produce that provide a premium price to the organic growers. Moreover, higher profitability of organic farming and use of environmentally sustainable organic inputs in the agriculture practices during the farming system make farms more competitive and climate-friendly. This low input agriculture strategy is not only helpful in improving food quality but also provide a great opportunity to the farmers to perform a low budget farming.

References

Bakonyi N, Bott S, Gajdos E, Szabo A, Jakab A, Toth B, Makleit P, Veres S (2013) Using biofertilizer to improve seed germination and early development of maize. Pol J Environ Stud 22(6):1595–1599

Barbieri P, Pellerin S, Nesme T (2017) Comparing crop rotations between organic and conventional farming. Sci Rep 7:13761. https://doi.org/10.1038/s41598-017-14271-6

Bhat S, Misra KK, Sharma VK (2017) Strategies of organic farming in fruit crops. J Pharmacogn Phytochem 6:2622–2629

Cacek T (1984) Organic farming: the other conservation farming system. J Soil Water Conserv 39:357–360

Cacek T, Linda LL (1986) The economic implications of organic farming. Am J Altern Agric 1(1):25–29

Chatterjee R, Gajjela S, Thirumdasu RK (2017) Recycling of organic wastes for sustainable soil health and crop growth. Int J Waste Resour 7:296. https://doi.org/10.4172/2252-5211.1000296

Devi HJ, Swamy NVC, Nagendra HR (2004) Effect of Agnihotra on the germination of rice seeds. IJTK 3(3):231–239

Erhart E, Hartl W (2010) Compost use in organic farming. In: Lichtfouse E (ed) Genetic engineering, Biofertilisation, soil quality and organic farming, Sustainable Agriculture Reviews, vol 4. Springer, Dordrecht

Fess TL, Benedito VA (2018) Organic versus conventional cropping sustainability: a comparative system analysis. Sustainability 10:272. https://doi.org/10.3390/su10010272

Gattinger A, Haeni M, Skinner C, Fliessbach A, Buchmann N, Mader P, Stolze M, Smith P, El-Hage Scialabba N, Niggli U (2012) Enhanced top soil carbon stocks under organic farming. Proc Natl Acad 109:18226–18231

Gerhardt RA (2012) A comparative analysis of the effects of organic and conventional farming systems on soil structure. Biol Agric Hortic 14:139–157

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012:1–15, Hindawi Publishing Corporation

Gopakkali P, Sharanappa (2014) Effect of organic farming practices on growth, yield, quality and economics of onion (*Allium cepa*) in dry zone of Karnataka. Indian J Agron 59:103–107

Gore NS, Sreenivasa MN (2011) Influence of liquid organic manures on growth, nutrient content and yield of tomato (*Lycopersicon esculentum* mill.) in the sterilized soil. Karnataka J Agric Sci 24:53–157

Kloepper JW (2003) A review of mechanisms for plant growth promotion by PGPR. In: Reddy MS, Anandaraj M, Eapen SJ, Sarma YR, Kloepper JW (eds) 6th international PGPR workshop (Abstracts and short papers), 5–10, Indian Institute of Spices Research. Calicut, India, pp 81–92

Lahoty P, Rana M (2013) Agnihotra Organic Farming. Pop Kheti 1(4):49–54

Pupaliene R, Sinkevicienė A, Jodaugienė D, Bajorienė K (2015) Weed control by organic mulch in organic farming system. In: Pilipavicius V (ed) Agricultural and biological sciences weed biology and control, ISBN 978-953-51-2131-2. https://doi.org/10.5772/60120

Raddy BS (2010) Organic farming: status, issues and prospects– a review. Agric AERA 23:343–358

Roychowdhury R, Banerjee U, Sofkova S, Tah J (2013) Organic farming for crop improvement and sustainable agriculture in the era of climate change. OJBS 13(2):50–65

Schutz L, Gattinger A, Meier M, Müller A, Boller T, Mader P, Mathimaran N (2018) Improving crop yield and nutrient use efficiency via biofertilization-a global meta-analysis. Front Plant Sci 12(8):2204. https://doi.org/10.3389/fpls.2017.02204

Singh AK, Singh G, Bhatt RP, Pant S, Naglot A, Singh L (2011) Sugars waste, an alternative growth and complete medium for fast growing *Rhizobium* cells. Afr J Microbiol Res 5:3289–3295

Somasundaram E, Amanullah MM (2007) Panchagavya on growth and productivity of crops: a review. Green Farming 1:22–26

Soni R, Sharma A (2016) Vermiculture technology: a novel approach in organic farming. Indian Hortic J 6:150–154

Soni R, Kumar A, Kanwar SS, Pabbi S (2017) Efficacy of liquid formulation of versatile rhizobacteria isolated from soils of Northern Western Himalayas on *Solanum lycopersicum*. IJTK 16(4):660–668

Steiner R (1924) Geisteswissenschaftliche Grundlagen zum Gedeihen der Landwirtschaft. Rudolf Steiner Verlag, Dornach

Turinek M, Grobelnik-Mlakar S, Bavec M, Bavec F (2009) Biodynamic agriculture research progress and priorities. Renewable Agric Food Syst 24(2):146–154

U.S. Department of Agriculture (1980) Report and recommendations on organic farming. Washington

Yadav SK, Babu S, Yadav MK, Singh K, Yadav GS, Pal S (2013) A review of organic farming for sustainable agriculture in northern India. Int J Agron 2013:1–8

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Perspectives of Seaweed as Organic Fertilizer in Agriculture

13

B. L. Raghunandan, R. V. Vyas, H. K. Patel, and Y. K. Jhala

Abstract

Seaweeds are the important marine resources available at negligible cost and rich in diverse bioactive compounds like lipids, proteins, carbohydrates, amino acids, phytohormones, osmoprotectants, mineral nutrients and antimicrobial compounds. They are key component in food, feed, and medicine since ancient times. Recent trend of organic farming has exploited the possible application of seaweed as organic/bio-fertilizer in agriculture. Many studies have demonstrated the benefits of seaweed in enhancing the plant growth and productivity. Added to this they are known to be a promising soil conditioner, protect the plants under abiotic and biotic stress and increase plant resistance against pest and diseases. In this chapter an attempt has been made to highlight the scientific progress on usefulness of seaweed in the context of utilization in agriculture as organic fertilizer and prospects for further research and use.

Keywords

Seaweeds · Organic farming · Soil conditioner · Stress · Resistance

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13.1 Introduction

Faster growth rate of world population has necessitated the increase in production of agro based products to achieve adequate food production. Among the various agro based products fertilizer is one of the critical inputs which influence the food production by sustaining soil health. In the present arena of organic agriculture the disadvantages of chemical fertilizers are apparent and farmers are turning towards eco-friendly alternative sources for plant nutrition resulting in huge demand for organic sources. To meet this ever increasing demand for organic sources of nutrients many viable alternatives have been explored commercially and one of such option is the use of seaweed as organic fertilizer in agriculture.

Generally seaweeds belong to assemblage marine algae which are of different shapes and sizes. The microscopic algae are phytoplankton and macroscopic ones are seaweeds. These are aquatic plants of the plant kingdom Thallophyta (Dhargalkar et al. 2001; Arioli et al. 2015) and grow in intertidal and subtidal area up to where 0.1% photosynthetic light is available. Seaweeds are one of the important marine creatures ecologically and economically important and attract unique attention with admirable qualities of being flexible, prolific and tenacious. Often these resources are considered as underutilized although many of the seaweeds have been a source of food, feed, industrial gums and therapeutics since ancient times (Dhargalkar and Pereira 2005). Many studies pertaining to plant growth promoting effects of seaweeds have been reported (Russo and Berlyn 1990; Zodape et al. 2011; Rao and Chatterjee 2014; Ali et al. 2016) and these have been proven as novel source of antioxidants, plant hormones, osmoprotectants, plant nutrients and other novel bioactive metabolites of pharmaceutical and industrial significance (Akila and Jeyadoss 2010; Ramarajan et al. 2013; Pacholczak et al. 2016a).

The use of seaweeds as organic fertilizer in agriculture compensate the deficiency and lack of plant nutrients like nitrogen, phosphorous and potassium and attract great potential for commercialization. The significance of seaweed as source of fertilizer in agriculture has been acknowledged by researchers worldwide. The feasibility of exploitation and utilization of sea weeds in agriculture is widely reported and different methods of preparations of sea weed as liquid fertilizer or powdered either whole or chopped are being employed. Recently scientists have been paid attention to novel and futuristic extraction methods such as enzyme assisted extraction, microwave assisted extraction, pressurized liquid extraction, supercritical fluid extraction and ultra sound assisted extraction which facilitate the better extraction of bioactive metabolites without degradation (Michalak and Chojnacka 2015). Seaweed extracts have been used as fertilizer additives and beneficial results from their use have been acknowledged (Kavipriya et al. 2011). With the use of seaweed extracts claims have been made for stimulation of seed germination, better root development, enhanced frost resistance, increased nutrient uptake, resistance to phytopathogenic fungi (Younes et al. 2009), bacteria (Alves et al. 2016), insects and other pests (Asha et al. 2012), higher yields with better restoration of plant health under high salinity conditions (Nabti et al. 2010) and superior performance of seaweed manure to conventional organic manure has been reported (Bokil et al. 1974).

Therefore there is increasing interest on seaweed as fertilizer or supplemental fertilizer where the significance is being given to the source of micronutrients and as a soil conditioner (Myklestad 1964). Moreover the use of seaweed is promising and contributes satisfactory solutions to overcome hazards caused by the extensive use of chemical fertilizers. However, the data pertaining to the complete details on nutrition, remediation biochemistry, novel bioactive metabolites and their activities are inadequate. This chapter presents the explanatory perspectives on the use of seaweed as organic fertilizer and other applications agriculture with future research prospects.

13.2 Seaweed Extract as Bioinput

The extract of seaweed known to contain wide range of bioactive compounds like trace elements, amino acids, antibiotics, auxins, gibberellins and vitamins which contribute to the beneficial feature of seaweed based organic manure. The method of extraction and species used could greatly influence the plant growth promotion activity. Many components of seaweed are reported to undergo seasonal variations which are being considered in commercial production and evaluation of seaweed organic manure.

The extraction methods are purpose intended and surprisingly there is lack of exact and comprehensive data about extraction procedures and techniques for agricultural purposes, mostly because the extraction and production protocols are rarely published and held as ownership dossier (Craigie 2011). In fact there are several reports citing extraction procedures have been ratified for agricultural biomolecules from seaweed. In many cases extracts are made by using water, acid, alkali or physical disruption by low temperature milling (Roj et al. 2009; Sharma et al. 2014). Among various methods being followed water based method seems to be the most cost effective and efficient in release of micro and macronutrients in adequate for the preparation of organic manure and biostimulant (Michalak and Chojnacka 2015). There are several reports claiming the biostimulant effect of water or alkaline extract of seaweed on cereals, pulses, vegetables and flowering plants (Kavipriya et al. 2011). Species reported to be used for the preparation of liquid seaweed fertilizer are *Ascophyllum nodosum*, *Fucus vesiculata, Furcelaria fastigiata, Hypnea musciformis, Sargassum plagiophyllum, Ulva lactuca, Durvillea potatorum, Sargassum wightii, Padina pavonica, Laminaria saccharina, Fucus seratus, Fucus vesiculosus, Padia tetrastomatica, Sargassum tenerrimum* and *Ecklonia radiate* (Dhargalkar and Pereira 2005).

13.3 Composition

The use of seaweed extract has witnessed the enhanced plant growth parameters in different crops as reported by many researchers and the mechanisms behind the stimulation of plant growth are not completely elucidated in many cases. Many studies have claimed the beneficial effects of seaweed extract due to vast array of constituents such as phytohormones, and plant nutrients (Karthikai Devi et al. 2009; Alam et al. 2014; Shahbazi et al. 2015; Mirparsa et al. 2016). Contrarily the organic matter content of the extract is known to influence plant growth (Davari et al. 2012). It was also established that application of different seaweeds as organic manures improved the soil condition and crop performance in field conditions (Badar et al. 2015). Seaweeds are known to add major plant nutrients N, P and K in addition to different micronutrients and trace elements in adequate required for the plant growth (Imbamba 1972; Tay et al. 1987; Sethi 2012; Mirparsa et al. 2016) (Tables 13.1 and 13.2). The analysis of mineral composition of different seaweed species belonging to different taxonomic groups like red, green and brown algae revealed the content of various minerals such as Ca, Mg, Na, K, Fe, Mn, Zn, Cu, Ni, Co, Cr, Cd (Anantharaman et al. 2010; El-Said and El-Sikaily 2013; Tuhy et al. 2015). Further, seaweeds are rich in diverse organic compounds *viz.,* proteins, amino acids, fiber, fat, cellulose, hemicelluloses, lignin and vitamins (Shevchenko et al. 2007; Mohammadi et al. 2013; Shri Devi and Paul 2014; Heltan et al. 2015; Mirparsa et al. 2016) and higher mineral composition in seaweeds compared to land vegetables has been documented (Manivannan et al. 2008; Kumar et al. 2009). Interestingly remarkable diversity of polysaccharides as constituents of cell walls and storage compounds in the cell has been reported by various workers (Murata and Nakazoe 2001; El-Deek and Mervat 2009; Heltan et al. 2015) (Table 13.3) which signifies the high level of soluble and insoluble fibers. The environmental condition influences the chemical composition as seasonal difference, temperature, salinity, light and availability of nutrients changes the composition to great extent (Karthikai Devi et al. 2009; Anantharaman et al. 2010; Hanan and Shimaa 2013). A significant difference in the composition was observed between the rainy winter and warm summer season (Benjama and Masniyom 2011). Further abundant diversity of carotenoids, chlorophyll and phycobiliproteins was also recorded (Chojnacka et al. 2012).

Table 13.1 Mineral composition of different seaweeds

Name of seaweed	Type	Nitrogen (mg/g)	Phosphorus (mg/g)	Potassium (mg/g)	References
Sargassum wightii	Brown algae	174.02	45.56	72.83	Divya et al. (2015a)
Dictyota dichotoma	Brown algae	175.02	44.56	71.84	Sasikumar et al. (2011)
Laurencia obtuse	Red algae	3.9	3.8	2.0	Safinaz and Ragaa et al. (2013)
Corallina elongate	Red algae	3.4	3.8	1.6	
Jania rubens	Red algae	4.0	3.5	1.6	
Ulva lactuca	Green algae	174.02	45.56	75.83	Divya et al. (2015b)

Table 13.2 Mineral composition of three genera of seaweed (Aslam et al. 2010)

Mineral compounds (ug/g of extract)	Red algae (*Lithothamnion calcareum*)	Green algae (*Ulva lactuca*)	Brown algae (*Stoechospermum marginatum*)
Copper	4.89	0.38	8.64
Manganese	57.50	62.00	8.75
Zinc	15.80	1.01	19.92
Iron	915.00	0.37	858.50
Potassium	5.17	113.00	29.65
Magnesium	25.80	18.30	9.60
Cobalt	0.08	0.06	3.47
Chromium	0.82	nd	16.60
Lead	0.15	nd	0.40
Nickel	1.84	10.40	25.20
Cadmium	0.07	2.00	5.90
Sodium	4.15	185.00	39.11
Calcium	351.50	195.26	2053.40
			
	Lithothamnion calcareum	*Ulva lactuca*	*Stoechospermum marginatum*

nd not detected

Table 13.3 Carbohydrates and amino acid composition of three genera of seaweed

	Red algae (Rhodophyceae)	Green algae (Chlorophyceae)	Brown algae (Phaeophyceae)
Polysaccharides	Agars,agaroids	Amylase	Alginates
	Carrageenans	Amylopectin	Cellulose
	Cellulose	Cellulose	Complex sulfated heteroglucans
	Complex mucilage's	Complex hemicelluloses	Fucose containing glycan
	Furcellaran	Glucomannans	Fucoidans
	Glycogen (floriden starch)	Mannans	Glucuronoxylofucans
	Mananas	Insulin	Laminarans
	Xylans, rhodymenan	Laminaran	Lichenan-like glucan
		Pectin	
		Sulfate mucilage (glucuronoxy lorhamnas), xylans	
Amino aciods			
Alanine	+++	+++	+++
Glycine	+++	++	++
Valine	++	++	++
Leucine	++	++	+
Serine	++	++	+
Threonine	+++	+++	+
Cystein	+	+	+
Methionine	+	+	+
Aspartate	+++	+++	++
Glutamate	+++	+++	++
Lysine	++	++	+
Arginine	+++	++	+
Phenylalanine	+	++	++
Tyrosine	+++	++	+
Proline	+++	+++	++
Histidine	+++	+	+

Adopted: Qasmi (1991), Castro-Gonzalez et al. (1996), Shevchenko et al. (2007), and Cian et al. (2015)

"+++" high quantity >60 mg/g total nitrogen; "++" average quantity 20–60 mg/g; "+" low quantity <20 mg/g

13.4 Seaweeds as Natural Bio-fertilizers

An adequate amount of macro and micronutrients, phytohormones and humic acids of seaweed make it as distinguished organic manure. Contrary to the ill effects of chemical fertilizers the seaweed derived fertilizer are biodegradable, non-toxic, non-polluting and non-hazardous to human beings, animals and birds. With the booming concern on residue free food the farmers are switching over to organic sources for plant nutrition. Besides increasing soil fertility the use of seaweed fertilizers enhances the moisture holding capacity, add adequate micronutrients for the plant growth thereby improve the soil structure (Dhargalkar and Pereira 2005). Seaweeds are known to contain various organic constituents such as polysaccharides, proteins and fatty acids which aid in moisture and nutrient retention in the soil thereby stimulating microorganisms' activity and improving soil texture. It has been established that seaweed based fertilizers facilitate conducive environment for root growth by enhancing the microbial diversity and activities like nutrient mineralization and mobilization (Selvaraj et al. 2004; Battacharya et al. 2015).

In recent times the spray application of plant nutrients has attracted considerable attention which increases the nutrient absorption efficiency has led to the generation of liquid based seaweed fertilizer. The liquid based fertilizers based on seaweed extracts originally developed by Milton in (1952) are extensively used in agriculture and horticulture (Srijaya et al. 2010; Shahbazi et al. 2015; Ciepiela et al. 2016). Many commercial products of seaweed based liquid fertilizer (Table 13.4) are available in the market. Seaweed extract are being used as a foliar spray, application to soil and for soaking seeds before sowing. Various claims have been documented over the beneficial effects of diluted extracts sprayed on plants in terms of improved plant health, increased plant growth, enhanced resistance to biotic and abiotic stresses and higher yield (Table 13.5). In few cases seaweeds were not only used as organic/bio-fertilizers but also as soil conditioners (Abdel-Raouf et al. 2012; Bhardwaj et al. 2014; Arioli et al. 2015). Improved crop growth and nutritional response had observed with the addition of fresh kelp (*Macrocystis integrifolia*) in fine texture soil (Temple and Bomke 1988). Nedzarek and Rakusa-Suszczewski (2004) has reported that mixture of macroalgae released adequate quantities of organic matter and different plant nutrients especially ammonium, nitrates, nitrite and phosphate. Further, growth promotion was observed in okra after foliar application (Abbasi et al. 2010), in *Vigna mungo* by *Sargassum myriocystum* extracts (Kalaivanan and Venkatesalu 2012), application of *Ulva fasciata* extract on wheat var. charman has witnessed higher seed germination, increased

Table 13.4 Commercially available seaweed products (Khan et al. (2009)

Product name	Seaweeds name	Applications
Acadian	*Ascophyllum nodosum*	Plant growth stimulant
Agri-Gro-Ultra	*Nodosum, Macrocystis pyrifera*	Plant growth stimulant
Agrokelp	*Ascophyllum nododum*	Plant growth stimulant
Bio-Genesis High Tide	Unspecified	Plant growth stimulant
Fartum	*Ecklonia maxima*	Biofertilizer
Kelpak	*Durvillea antarctica*	Plant growth stimulant
Profert	Unspecified	Plant biostimulant
Sea winner	*Durvillea potatorum*	Plant biostimulatant
Sasol	Unspecified	Plant growth stimulant
Somzyme SL (India)	*Sargassum weightii*	Biostimulant
Sagarika (India)	*Kappaphycus alvarezii*	Plant growth promoter

Table 13.5 Illustrations of seaweed application in various crops

Sl No	Seaweed	Crop	Effect	References
1	*Phormidium foveolarum*	Rice	Increased germination percentage	Booth (1969)
2	*Sargassum wightii*	*Zizyphus mauritiana*	Increased size and quality of fruits	Rama Rao (1991)
3	*Sargassum plagiophyllum*	Blackgram, greengram	Increased germination and enhanced seedling growth	Venkataraman et al. (1993)
4	*Ecklonia maxima*	Marigold	Improved growth and flower yield	Staden et al. (1994)
5	*Ulva lactuca*	*Vigna ungiculata*	Increased fresh and dry weight and enhanced accumulation of nitrogen and phosphorus	Sekar et al. (1995)
6	*Cladophora dalmatica, Enteromorpha intestinalis, Ulva lactuca, Corallina mediterranea, Jania rubens, Pterocladia pinnata*	*Vicia faba*	Increased seed germination and seedling growth, higher total soluble sugars, protein and cholorophyll content	El-Sheekh and EI-Saied (2000)
7	*Ulva lactuca*	Chilli and pea nut	Increased growth and yield attributes	Sridhar and Rengasamy (2002, 2010a)
8	*Asparagopsis taxiformis*	*Phaseolus aureus*	Increased root and internodal length, increased leaf surface area	Renuka Bai et al. (2007)
9	*Gracilaria corticata*	Black gram	Increased shoot and root dry weight, chlorophyll and protein content	Ayun Vinuba et al. (2008)
10	*Ulva lactuca*	*Brassica juncea, Phaseolus mungo, Trigonella foenum*	Increased seedling growth	Rajasulochana et al. (2008)
11	*Rosenvigea intricate*	Okra	Improved seedling growth, fruit yield and chlorophyll content	Thirumaran et al. (2009)
12	*Kappaphycus alvarezii*	Tomato and okra	Increase in number and size of fruits and yield and nutritional quality of fruits	Zodape et al. (2011)

(continued)

Table 13.5 (continued)

Sl No	Seaweed	Crop	Effect	References
13	*Ascophyllum nodosum*	Onion	Improved growth and yield parameters with low downy mildew incidence	Dogra and Mandradia (2012)
14	*Ascophyllum nodosum*	Brinjal	Enhanced growth	Bozorgi (2012)
15	*Laurencia obtusa, Corallina elongata, Jania rubens*	Maize	Increased plant height, number of leaves and increase in K uptake	Safinaz and Ragaa (2013)
16	*Caulerpa peltata, Gracilaria corticata*	Green gram	Enhanced seed germination, growth and chrolophyll	Chitra and Sreeja (2013)
17	*Ascophyllum nodosum*	Grape	Improved vegetative growth	Popescu and Popescu (2014)
18	*Ulva lactuca, Caulerpa sertularioides, Padina gymnoposra, Sargassum liebmannii*	Tomato	Better seed germination, greater plumule and radical length and seedling vigour	Rosalba Mireya Hernández-Herrera et al. (2014)
19	*Sargassum crassifolium*	Tomato	Enhanced growth, root & shoot dry weight and fruit number	Sutharsan et al. (2014)
20	*Padina vickersiae, Enteromorpha compress, Ulva fasciata, Gelidium crinale, Jania rubens, Laurencia obtusa*	Maize	Improved growth, yield and grain quality	Fatma et al. (2014)
21	*Gracilaria textorii, Hypnea musciformis*	Brinjal, tomato and chilly	Increased seed germination, growth and yield parameters	Rao and Chatterjee (2014)
22	*Stoechospermum marginatum*	Brinjal	Higher fruit yield and fruit weight	Sivasangari Ramya et al. (2015)
23	*Laurencia pinnatifida, Sargassum duplicatum, Caulerpa scapelliformis*	*Vinga Mungo*	Enhanced seed germination	Emmanuel et al. (2015)
24	*Ulva rigida, Fucus spiralis*	Beans	Enhanced vegetative growth under drought stress condition	Mounir et al. (2015)
25	*Kappaphycus alvarezii, Gracilaria* sp.	Rice	Increased growth, yield attributes and higher chlorophyll content	Devi and Mani (2015)
26	*Sargassum wightii*	Brinjal	Enhanced germination, growth and productivity	Divya et al. (2015a, b)

(continued)

Table 13.5 (continued)

Sl No	Seaweed	Crop	Effect	References
27	*Codium tomentosum, Sargassum vulgare*	Wheat	Increased germination, seedling growth, chlorophyll and carotenoids content	Mohy El-Din (2015)
28	*Sargassum wightii, Ulva lactuca, Enteromorpha intestinalis*	*Glycine max*	Enhanced seed germination, growth and biochemical features	Mathur et al. (2015)
29	*Ascophyllum nodosum*	Tomato	Increase in plant height and fruit yield	Ali et al. (2016)
30	*Gracilaria corticata, Kappaphycus alvarezii*	Brinjal and tomato	Improved seed germination	Rinku et al. (2017)

growth parameters, pigment and carbohydrate content (Shahbazi et al. 2015), increase in root and shoot length and number of leaves with the application of seaweed sap in maize and rice (Singh et al. 2015a, b, 2016). Recently the overall growth promotion of *Vigna* sp. by using different seaweed extracts as biofertilizers has been documented (Reddy et al. 2016).

The regulatory effect on phytohormone synthesis and accumulation was observed with the application of commercially available extract of *Ascophyllum nodosum* on *Arabidopsis* (Wally et al. 2012) and also the induction of cytokinin like activity with the application of brown alga *Ascophylum nodosum* extracts on *Arabidopsis thaliana* (Khan et al. 2011). Various studies regarding the stimulation of plant growth by seaweed extract and their composition admitted that they are rich source of plant growth regulators such as indole acetic acid (IAA), kinetin, zeatin, gibberellins, cytokinin, ethylene and abscisic acid (Kingman and Moore 1982; Nelson and Van Staden 1985; Tarakhovskaya et al. 2007; Zhang and Ervin 2008; Zodape et al. 2008). In parallel similar explanations were elaborated on richness of phytohormones in seaweed extract and possible role in plant growth promotion (Sridhar and Rengasamy 2010b). Moreover, there are evidences of combined application of *Azotobacter chrococcum* and *Bacillus megaterium* var. *phosphaticum* with seaweed extracts enhancing the plant growth and productivity in bitter orange (Ismail et al. 2011) and application of *Azospirillum brasilense* with *Ulva lactuca* extracts improved the growth of durum wheat under saline and non-saline conditions (Nabti et al. 2010). Utilization of seaweed based fertilizers was reported to reduce the doses of nitrogen, phosphorus and potash fertilizers. Nearly 59 species of seaweeds are known to stimulate growth and yield of various crops (Sunarpi et al. 2010) (Table 13.5) and induce seed germination and growth parameters strongly than chemical fertilizers (Partani 2013).

13.5 Seaweeds as Soil Conditioner

The trend of seaweed utilization was rooted in 1951 in European countries and the seaweeds were used directly or in composted form with farmyard manure as soil conditioner to increase crop productivity in coastal areas and for recovery of alkaline soils where deficiency diseases are frequent (Rama Rao 1992; Booth 1969). Seaweeds had been used since ancient times by mixing with sand or soil or composted with organic sources like peat, straw, etc., (Craigie 2011). The scope of utilization of seaweeds has been expanded in agriculture domain attributed to the beneficial effects of seaweeds as organic source of nutrients (Chapman 1980; Nelson and Van Staden 1984).

More than 50 years ago it has been reported that brown seaweeds such as *Sargassum* were used to fertilize the soil and further they supplemented organic matter to the soil due to the decomposition of soluble alginates present (Thivy 1964). In case of clay soils with low organic matter which are not porous and lack crumby structure, addition of seaweeds adds humic acid and to a greater extent the polysaccharide alginates create crumby structure by binding with larger clay aggregates or by combining chemically with metallic radicals of the soil (Zodape 2001). Despite the fact that the seaweeds had been utilized originally as soil conditioner, in recent times seaweeds received worldwide attention as organic/bio-fertilizers to supplement plant nutrients (Aitken and Senn 1964) and being applied in different formulation such as foliar spray, granules, powder and manure (Kumari et al. 2011, 2013; Gharakhani et al. 2016). Recent trend of organic farming and demand for organic foods has created an immense opportunity to reexamine the promising applications of seaweed extracts as natural fertilizer, soil conditioner and biostimulant (Khan et al. 2009).

13.6 Phytohormones of Seaweeds

Since ancient times seaweeds and their extracts have been used to improve the plant growth and stress tolerance. In fact the plant growth promoting substances of sea weed known to influence biosynthetic pathways of phytohormone in plants (Wally et al. 2012; Divya et al. 2015a, b) and rich amount of auxins (IAA, IBA), gibberellins, cytokinins and osmoprotectant betains, micronutrients, vitamins, aminocids and antibiotics boost the growth and yield of various vegetable and fruit crops (Renuka Bai et al. 2007; Mathur et al. 2015; Pacholczak et al. 2016b).

Many studies have documented the possible role of phytohormones of seaweed extract in plant growth. Zodape et al. (2010) reported the role of cytokinin in plant growth regulation. The extracts of the sea weed *Ascophyllum nodosum* have been utilized in enhancing the production and productivity in various agricultural ecosystems (Rayorath et al. 2008b). The analyzed extracts of *Ascophyllum nodosum* acknowledged the high amount of cytokinins (CKs) particularly trans-zeatin type CK and abscisic acid (Wally et al. 2012). Rayorath et al. (2008a) described that the organic components of *Ascophyllum nodosum* induces amylase activity in barley. Gibberellic acid (GA_3) induces hydrolytic enzymes in the aleurone layer of endosperm which facilitate enhanced seed germination. It is known that the green and brown algae are rich in gibberellic acid which acts as a signal in seed germination process by activating amylase genes in aleurone cells of seed (Sun and Gubler 2004).

Further it is claimed that the application of seaweed extracts increases water and nutrient uptake in plant resulting improved plant growth (Russo and Berlyn 1990). Thus the cultivation and utilization of seaweed is an efficient and profitable approach in agriculture (Sridhar and Rengasamy 2011; Gireesh et al. 2011). It is known that the sea weed extracts influence various aspects of plant growth and development (Ismail and El-Shafay 2015). The oxidative stress during drought condition increases cell membrane leakage in the plants and which needs enzymatic or non-enzymatic antioxidant activities. Kasim et al. (2015) evaluated the physiological effects of application of *Sargassum latifolium, Ulva lactuca* extracts on *Triticum aestivum* during drought. Pretreatment of extract managed to alleviate damaging effects of drought on vegetative stage of wheat and suggested the direct activation of antioxidative system (catalase, peroxidase and ascorbate) and also the role of phytohormones and micronutrients in antagonizing oxidative damage. Added the seaweed extracts are known to restore plant growth in high pH, temperature conditions (Briceno-Domınguez et al. 2014), low pH and water stress conditions (Arthur et al. 2013). Generally these findings have reported that the phytohormone (cytokinin, gibberellic acid and abscisic acid) content of seaweed extracts help to support the plant under stress condition and recover the plants (Reitz and Trumble 1996; El-Shoubaky and Salem 2016).

13.7 Osmoprotective Effect of Seaweeds for Stress Management

In arid and semiarid region salinity constitutes a major hurdle for agriculture. Primarily the salt stress affect the plant growth parameters such as seed germination (Sharma et al. 2004), photosynthesis and transpiration (Sharma et al. 2005), biosynthesis of phytohormones and plant growth regulators (Sarin and Narayanan 1968). Salinity also affects the plant growth promoting rhizobacteria (PGPR) as rhizospheric microbes play a significant role in soil processes influencing plant growth and yield (Tilak et al. 2005). Hence, osmotolerant PGPR were applied to encourage the salt tolerance through osmolegulatory mechanisms (Hartmann et al. 1991; Miller and Wood 1996). However, due to richness and diversity of osmoprotective molecules, seaweeds could be successfully used to ameliorate the salt stress affecting the plant growth. Because of high salinity in marine environment seaweeds exposed to continuous slat stress and under this hyperosmotic conditions compounds such as proline, betaines, polyamines and sorbitol are synthesized and accumulated at high concentrations which are closely associated with salt stress tolerance in seaweeds (Van Alstyne et al. 2003; El-Shoubaky and Salem 2016; Van Bergeijk et al. 2002). It is also found that many marine algae produce a dominant osmoprotective compound 3-dimethylsulfoniopropionate (DMSP) and its degradation product dimethylsulfide play a key role in biogeochemical sulfur cycle (Summers et al. 1998) and reported as competent osmoprotectant for soil bacteria and plants (Asma et al. 2006; Rezaei et al. 2012; Manaf 2016). It is demonstrated that use of *Ulva lactuca* extract under salt stress condition was able to restore the leaf area and content in soybean (Ramarajan et al. 2013) and addition of extracts of *Sargassum vulgare* enhanced the germination of *Phaseolus vulgaris* under salt stress (Latique et al. 2014). Other distinguished findings of successful use of seaweed extracts are: use of extracts of *Ascophyllum nodosum* to *Amaranthus tricolor* enhancing flowering (Abdel Aziz et al. 2011), stimulation of germination and growth of tomato seedlings (Alalwani et al. 2012), application of *Ulva lactuca* restoring the growth of durum wheat under high salinity (Nabti et al. 2007, 2010) and *Durvillaea plantarum* application improving the growth and yield of bean plants under water stress (Bastos et al. 2016)

13.8 Biological Control Potential of Seaweeds

As the seaweeds gained attention as organic fertilizer or soil conditioner in the past, there were studies demonstrated the potential of seaweed extracts in inducing resistance in plants against pest and diseases. Booth (1966) noticed the reduction in incidence of *Botrytis* infection in strawberries with the application of seaweed extract and similar findings were reported on virtual elimination of black spots in rose, less mildew and green peach potato aphid on turnip leaves, reduced incidence of damping off in tomato seedlings (Stephenson 1966), low incidence of aphid in sugarbeet, reduced population of red spider mite in chrysanthemum and low incidence of brown rot in peaches sprayed with seaweed extract. It is generally established that seaweeds are rich source of diverse natural bioactive molecules *viz.,* terpenes, steroids, aromatics like acetogenins, aminoacid derived compounds phlorotannin and other polymeric substances (Ozdemir et al. 2004; Zbakh et al. 2012; Thinakaran and Sivakumar 2013; Shri Devi and Paul 2014). Moreover seaweed produce rich bioactive metabolites in response to microbial activities (Taskin et al. 2007; Alam et al. 2014; Watee et al. 2015; Perez et al. 2016).

Several studies have been conducted to evaluate the antimicrobial activities of seaweed extracts. Presence of terpenes in the extracts has been attributed to the antifungal activities (Paulert et al. 2009; Peres et al. 2012). Similarly Khallil et al. (2015) tested the efficacy of six organic extracts of five brown algae viz., *Sargassum vulgare, Cystoseira barbata, Dictyopteris membranaceae, Dictyo dichotoma* and *Calpomenia sinuosa* against fungal phytopathogens (*Alternaria alternata, Cladosporium cladosporioides, Fusarium oxysporum, Epicoccum nigrum, Aspergillus niger, Aspergillus flavus* and *Penicillium citratum*) and the findings showed the pronounced antifungal activity of seaweed extracts. Many of green algae like *Ulva fasciata* and *U. lactuca* also showed the efficacy against nymphs and adults of red cotton bug (*Dysdercus cingulatus*) (Asha et al. 2012). Added many brown seaweed species are known to control plant diseases (Peres et al. 2012).

Extracts of different marine algal species like *Sargassum tenerrimum*, *Padina tetrastromatica* and *Melanothamnus afaqhusainii* showed nematicidal activity against root knot nematode *Meloidogyne javanica* (Khan et al. 2015). Recent findings have revealed that the bioactive compounds *viz.*, polysaccharides, fatty acids, tannins, pigments, lectins, alkaloids, terpenoids and halogenated compounds extracted from green, brown and red algae were promising in controlling root infecting fungi in okra seedlings (Perez et al. 2016; Sultana et al. 2005). Foliar application of seaweed extracts found to inhibit fruit rot with increase in yield of strawberry (Washington et al. 1999). The use of extracts of *Ascophyllum nodosum* to carrot plants resulted in significant inhibition of *Botrytis cinerea* with parallel increase in the activity of defense enzymes such as peroxidase, polyphenoloxidase, phenylalanine ammonia lyase, chitinase, β-1,3-glucanase (Jayaraj et al. 2008). However detailed assessments on effects of seaweed extracts in controlling pest and disease is need to be performed to establish direct inhibition of the pathogen and induction of systemic resistance in the plants.

13.9 Bio-remediation of Polluted Soils by Seaweed

It is known that heavy metal ions such as cadmium and lead are successfully removed using seaweed biomass as adsorbents (Vinoj Kumar and Kaladharan 2006). Hence the seaweed could be scientifically exploited as adsorbents and by virtue of macroscopic structure facilitate the successful production of biosorbent particles suitable for biosorption (Vieira and Volesky 2000). Recently various methods have been used to characterize the mechanisms underlying the biosorption of heavy metals by seaweeds.

Heavy metal adsorption studies using *Kappaphycus* sp. in aqueous solution revealed the possibility of seaweed in removal of heavy metal ions from aqueous solution (Rahman and Sathasivam 2015). Further it is found that many types of seaweed such as *Gracilaria corticata varcartecala* and *Grateloupia lithophila* were able to eliminate heavy metal (Cr(VI), Cr(III), Hg(II), Pb(II), Co and Cd(II)) toxicity by biosorption (Tamilselvan et al. 2013; Duraipandian et al. 2016). Mixture of green, red and brown algae were prepared to remove chromium toxicity and the material analysis conceded the two functional groups of polysaccharides of seaweed surface involved in adsorption (Abirami et al. 2013). Similarly there are reports citing the successful utilization of seaweed such as *Kappaphycus alvarezii* and *Eucheuma denticulatum* in cadmium (II) biosorption (Kang et al. 2012) and red algae extract Acadian was used to discharge lead (Pb) toxicity (Abdalla and El-Khoshiban 2012).

13.10 Constraints of Seaweed Application

Hitherto there are no serious issues of limitations on seaweeds as organic/bio-fetilizers. However, high salt content of seaweeds and long term utilization may cause salinity problems. Such problems can be prevented by adopting intermittent pauses of seaweed application and allow rain rinsing period to reduce salt content (Angus and Dargie 2002; MacArtain et al. 2007) and use of purified preparations may reduce this problem. Further, seaweeds are effective heavy metal accumulators in the marine and other environments (Karthicka et al. 2012; Sudharsan et al. 2012), the utilization of seaweeds of contaminated sites as soil conditioner or fertilizer would increase the contaminants in soil and plants as well (Wosnitza and Barrantes 2003). Thus contamination levels of seaweed need to be checked before application. Furthermore, sulfides formed as the result of anaerobic degradation of sulfur compounds in seaweed may create the soil acidification as the sulfides undergo microbial oxidation to sulfates (Brady and Weil 2008). The unique organic constituents of seaweed *viz*., carageenans, laminarins and ulvans are distinct from the major plant polymeric carbon compounds such as cellulose, hemicelluose and lignin and soil microbial community experience these novel and possibly the resistant compounds for biodegradation (Jaulneau et al. 2010). In such circumstances detailed examination of long term utilization of seaweeds on native soil microbial community should be carried out. Moreover, the seaweeds are also known to colonize diverse microbial community which produces antimicrobial compounds (Egan et al. 2013). Hence, it is very important to ascertain the extent of this microbial community establishment in the soil. The introduced microbial community associated with seaweed may improve the nutrient turnover in soil which could be the basis for improved plant and soil health.

13.11 Conclusion

In the chapter special emphasis was given on role and utilization of seaweed in agricultural and food security as natural fertilizer, soil conditioner and biocontrol agent for soil and plant health. The present era of organic agriculture and demand for organic foods has created the new realm of biological inputs in agriculture. In this context seaweed based fertilizers have gained greatest attention and created the new opportunities being low cost input to reinvestigate in agriculture. It is well demonstrated that seaweeds are rich sources of bioactive compounds which make them selectively chosen for agriculture and as dietary supplement in human food and feed for animals, in dairy, leather, textile and pharmaceutical etc. industries. Moreover in spite of these significant findings dedicated efforts are required to elucidate possible microbiological and ecological interactions of seaweeds which will provide the basis for aggressive utilization of seaweeds in agriculture and allied sectors for human welfare.

References

Abbasi FF, Baloch MA, Aia-ulhassan WKH, Shah AN, Rajpar I (2010) Growth and yield of okra under foliar application of some new multinutrient fertilizer products. Pak J Agric Agric Eng Vet Sci 26:11–18

Abdalla MM, El-Khoshiban N (2012) The palliative effect of bioorganic fertilizer on lead pollution in *Lycopersicum esculentum* plants. J Basic Appl Sci 8:399–410

Abdel Aziz NG, Mahgoub MH, Siam HS (2011) Growth, flowering and chemical constituents performance of *Amaranthus tricolor* plants as influenced by seaweed (*Ascophyllum nodosum*) extract application under salt stress conditions. J Appl Sci Res 7:1472–1484

Abdel-Raouf N, Al-Homaidan AA, Ibrahem IBM (2012) Agricultural importance of algae. Afr J Biotechnol 11:11648–11658

Abirami S, Srisudha S, Gunasekaran P (2013) Comparative study of chromium biosorption using brown, red and green macroalgae. Int J Biol Pharm Res 4:115–129

Aitken JB, Senn TL (1964) Seaweed products as a fertilizer and soil conditioner for horticultural crops. Bot Mar 8:144–148

Akila N, Jeyadoss X (2010) The potential of seaweed liquid fertilizer on the growth and antioxidant enhancement of *Helianthus annuus* L. Orient J Chem 26:1353–1360

Alalwani BA, Jebor MA, Hussain TAI (2012) Effect of seaweed and drainage water on germination and seedling growth of tomato (*Lycopersicon* spp.). Euphrates J Agric Sci 4:24–39

Alam ZM, Braun G, Norrie J, Hodges DM (2014) *Ascophyllum* extract application can promote plant growth and root yield in carrot associated with increased root-zone soil microbial activity. Can J Plant Sci 94:337–348

Ali N, Aidan F, Adesh R, Jayaraj J (2016) The effect of *Ascophyllum nodosum* extract on the growth, yield and fruit quality of tomato grown under tropical conditions. J Appl Phycol 28:1353–1362

Alves RC, Merces PFF, Souza IRA, Alves CMA, Silva APSA, Lima VLM, Correia MTS, Silva MV, Silva AG (2016) Antimicrobial activity of seaweeds of Pernambuco, northeastern coast of Brazil. Afr J Microbiol Res 10:312–318

Anantharaman P, Karthikaidevi G, Manivannan K, Thirumaran G, Balasubramanian T (2010) Mineral composition of marine macroalgae from mandapam coastal regions-southeast coast of India. Rec Res Sci Technol 2:66–71

Angus S, Dargie T (2002) The UK Machair habitat action plan: progress and problems. Bot J Scotl 54:63–74

Arioli T, Mattner SW, Winberg PC (2015) Applications of seaweed extracts in Australian agriculture: past, present and future. J Appl Phycol 27:2007–2015

Arthur GD, Aremu AO, Moyo M, Stirk WA, Van Staden J (2013) Growth promoting effects of a seaweed concentrate at various pH and water hardness conditions. S Afr J Sci 109:1–6

Asha A, Rathi JM, Raja PD, Sahayaraj K (2012) Biocidal activity of two marine algal extracts against third instar nymph of *Dysdrcus cingulatus* (Fab.) (Hemiptera, Pyrrhocoridae). J Biopest 5:129–134

Aslam MN, Kreider JM, Paruchuri T, Bhagavathula N, DaSilva M, Zernicke RF, Goldstein SA, Varani J (2010) A mineral-rich extract from the red marine algae *Lithothamnion calcareum* preserves bone structure and function in female mice on a western-style diet. Calcif Tissue Int 86:313–324

Asma M, Muhammad S, Nudrat AA (2006) Influence of exogenously applied glycine betaine on growth and gas exchange characteristics of maize (*Zea mays* L.). Pak J Agric Sci 43:36–41

Ayun Vinuba, Pinky VR, Prakash JW (2008) Effects of seaweed extract on growth and biochemical parameters of black gram. Plant Arch 8(1):211–214

Badar R, Khan M, Batool B, Shabbir S (2015) Effects of organic amendments in comparison with chemical fertilizer on cowpea growth. Int J Appl Res 1:66–71

Bastos FJC, Soares FAL, Sousa CV, Tavares CJ, Teixeira MB, Sousa AEC (2016) Common bean yield under water suppression and application of osmoprotectants. Rev Bras Eng Agric Ambient 20:697–701

Battacharya D, Babbohari MZ, Rathor P, Prithiviraj B (2015) Seaweed extracts as biostimulants in horticulture. Sci Hortic 196:39–48

Benjama O, Masniyom P (2011) Nutritional composition and physicochemical properties of two green seaweeds (*Ulva pertusa* and *U. intestinalis*) from the Pattani Bay in Southern Thailand. Songklanakarin J Sci Technol 33:575–583

Bhardwaj D, Wahid Ansari M, Kumar RS, Tuteja N (2014) Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microb Cell Fact 13:13–66

Bokil KK, Mehta VC, Datar DS (1974) Seaweeds as manure; pot culture manorial experiments on wheat. Phykos 13:1–5

Booth E (1966) Some properties of seaweed manures. In: Proceeding of fifth international seaweed symposium, Halifax, pp 349–357

Booth E (1969) The manufacture and properties of seaweed extracts. In: Proceeding of sixth international seaweed symposium, La marina Merchante, Madrid Spain, pp 655–662

Bozorgi HR (2012) Effects of foliar spraying with marine plant *Ascophyllum nodosum* extract and nano iron chelate fertilizer on fruit yield and several attributes of eggplant (*Solanum melongena* L.). ARPN J Agric Biol Sci 7:357–362

Brady NC, Weil R (2008) The nature and properties of soils, 14th edn. Pearson Prentice Hall, Upper Saddle River

Briceno-Domınguez D, Hernandez-Carmona G, Moyo M, Stirk W, Van Staden J (2014) Plant growth promoting activity of seaweed liquid extracts produced from *Macrocystis pyrifera* under different temperature conditions. J Appl Phycol 26:2203–2210

Castro-Gonzalez MI, Oeriz-Gil FR, Perez-Estrella S, Carrillo-Dominguez S (1996) Chemical composition of the green alga *Ulva lactuca*. Cienc Mar 22:205–213

Chapman DJ (1980) Seaweeds and their uses, 3rd edn. Chapman and Hall, London

Chitra G, Sreeja PS (2013) A comparative study on the effect of seaweed liquid fertilizers on the growth and yield of *Vigna radiata* (L.). Nat Environ Pollut Tech 12(2):359–362

Chojnacka K, Saeid A, Witkowska Z, Tuhy L (2012) Biological active compounds in seaweeds extracts—the prospects for the application. Open Conf Proc J 3:20–28

Cian RE, Drago SR, Medina FS, Martı'nez-Augustin O (2015) Proteins and carbohydrates from red seaweeds: evidence for beneficial effects on gut function and microbiota. Mar Drugs 13:5358–5383

Ciepiela GA, Godlewska A, Jankowska J (2016) The effect of seaweed *Ecklonia maxima* extract and mineral nitrogen on fodder grass chemical composition. Environ Sci Pollut Res 23:2301–2307

Craigie JS (2011) Seaweed extract stimuli in plant science and agriculture. J Appl Phycol 23:371–393

Davari M, Sharma SN, Mirzakhani M (2012) Residual influence of organic material, crop residues, and biofertilizers on performance of succeeding mung bean in an organic rice-based cropping system. Int J Recycl Org Waste Agric 1:1–14

Devi NL, Mani S (2015) Effect of seaweed saps *Kappaphycus alvarezii* and *Gracilaria* on growth, yield and quality of rice. Indian J Sci Technol 8(19):74–84

Dhargalkar VK, Pereira N (2005) Seaweed: promising plant of the millennium. Sci Cult 71:60–66

Dhargalkar VK, Untawale AG, Jagtap TG (2001) Marine macroalgal diversity along the Maharashtra coast: past and present status. Indian J Mar Sci 30:18–24

Divya K, Roja MN, Padal SB (2015a) Effect of seaweed liquid fertilizer of *Sargassum wightii* on germination, growth and productivity of brinjal. Int J Adv Res Sci Eng Technol 2:868–871

Divya K, Roja MN, Padal SB (2015b) Influence of seaweed liquid fertilizer of *Ulva lactuca* on the seed germination, growth, productivity of *Abelmoschus esculentus* (L). Int J Pharmacol Res 5:344–346

Dogra BS, Mandradia RK (2012) Effect of seaweed extract on growth and yield of onion. Int J Farm Sci 2(1):59–64
Duraipandian M, Sevugaperumal R, Ganesh D, Ramasubramanian V (2016) Establishment of the biosorptive properties of *Ulva lactuca* subjecting *Eleusine coracana* (L) gaertn to heavy metal stress by cobalt. JOAASR 1:7–17
Egan S, Harder T, Burke C, Steinberg P, Kjelleberg S, Thomas T (2013) The seaweed holobiont: understanding seaweed-bacteria interactions. FEMS Microbiol Rev 37:462–476
El-Deek AA, Mervat AB (2009) Nutritional and biological evaluation of marine seaweed as a feedstuff and as a pellet binder in poultry diet. Int J Poul Sci 8:875–881
El-Said GF, El-Sikaily A (2013) Chemical composition of some seaweed from Mediterranean Sea coast, Egypt. Environ Monit Assess 185:6089–6099
El-Sheekh MM, El-Saied AEDF (2000) Effect of crude seaweed extracts on seed germination, seedling growth and some metabolic processes of *Vicia faba* L. Cytobios 101(396):23–35
El-Shoubaky GA, Salem EA (2016) Effect of abiotic stress on endogenous phytohormones profile in some seaweeds. IJPPR 8:124–134
Emmanuel JSS, Lakshmikandan M, Vasanthakumar P, Sivaraman K (2015) Improved seedling growth and seed germination in legume crop *Vigna mungo* (L.) utilizing marine macro algal extracts. Proc Nat Acad Sci India Sec B Biol Sci 85(2):643–651
Fatma M, Al-Shakankery RA, Hamonda AMM (2014) The promotive effect of different concentrations of marine algae as biofertilizers on growth and yield of maize (*Zea mays* L.) plants. J Chem Biol Phy Sci Sec B 4(4):3201–3211
Gharakhani H, Mirhadi SM, Yazdandoost M (2016) The effect of different foliar application amount and different times of seaweed using (Acadian) on potato yield and yield components. J Curr Res Sci 1:23–27
Gireesh R, Haridevi CK, Salikuty J (2011) Effect of *Ulva lactuca* extract on growth and proximate composition of *Vigna unguiculata*. Walp J Res Biol 8:624–630
Hanan MK, Shimaa ME (2013) Seasonal variations in the biochemical composition of some common seaweed species from the coast of Abu Qir Bay, Alexandria, Egypt. Oceanologia 55:435–452
Hartmann A, Prabu SR, Galinski EA (1991) Osmotolerance of diazotrophic rhizospheric bacteria. Plant Soil 137:105–109
Heltan MM, Wakibia JG, Kenji GM, Mwasaru MA (2015) Chemical composition of common seaweeds from the Kenya Coast. J Food Res 4:28–38
Imbamba SK (1972) Mineral element content of some benthic marine algae of the Kenya Coast. Botan Marina 17:113–115
Ismail MM, El-Shafay SM (2015) Variation in taxonomical position and biofertilizing efficiency of some seaweed on germination of *Vigna unguiculata* (L). IJESE 6:47–57
Ismail OM, Dakhly OF, Ismail MN (2011) Influence of some bacteria strains and algae as biofertilizers on growth of bitter orange seedlings. Aust J Basic Appl Sci 5:1285–1289
Jaulneau V, Lafitte C, Jacquet C, Fournier S, Salamagne S, Brian X, Esquerre-Tugaye M-T, Dumas B (2010) Ulvan, a sulfated polysaccharide from green algae, activates plant immunity through the jasmonic acid signaling pathway. J Biomed Biotechnol. https://doi.org/10.1155/2010/52529
Jayaraj J, Wan A, Rahman M, Punja ZK (2008) Seaweed extract reduces foliar fungal diseases on carrot. Crop Protect 27:1360–1366
Kalaivanan C, Venkatesalu V (2012) Utilization of seaweed *Sargassum myriocystum* extracts as a stimulant of seedlings of *Vigna mungo* (L.) Hepper. Span J Agric Res 10:466–470
Kang OL, Nazaruddin R, Musa A (2012) Cadmium (II) biosorption onto seaweed (*Kappaphycus alvarezii* and *Eucheuma denticulatum*) waste biomass: equilibrium and mechanism studies. Middle-East J Sci Res 11:867–872
Karthicka P, Siva Sankarb R, Kaviarasanb T, Mohanrajua R (2012) Ecological implications of trace metals in seaweeds: bioindication potential for metal contamination in Wandoor, South Andaman Island. Egypt J Aquat Res 38:227–231

Karthikai Devi G, Thirumaran G, Manivannan K, Anantharaman P (2009) Element composition of certain seaweeds from Gulf of Mannar marine biosphere reserve, southeast coast of India. World J Dairy Food Sci 4:46–55
Kasim WA, Hamada EAM, Shams El-Din NG, Eskander SK (2015) Influence of seaweed extracts on the growth, some metabolic activities and yield of wheat grown under drought stress. Int J Agri Agri Res 7:173–189
Kavipriya R, Dhanalakshmi PK, Jayashree S, Thangaraju N (2011) Seaweed extract as a biostimulant for the legume crop green gram. J Ecobiotechnol 3:16–19
Khallil AM, Daghman IM, Fady AA (2015) Antifungal potential in crude extracts of five selected brown seaweeds collected from the Western Libya Coast. J Micro Creat 1:1–8
Khan W, Rayirath UP, Subramanian S, Jithesh MN, Rayorath P, Hodges DM, Critchley AT, Craigie JS, Norrie J, Prithiviraj B (2009) Seaweed extracts as biostimulants of plant growth and development. J Plant Growth Regul 28:386–399
Khan K, David H, Alan TC, Balakrishnan P (2011) Bioassay to detect *Ascophyllum nodosum* extract-induced cytokinin-like activity in *Arabidopsis thaliana*. J Appl Phycol 23:409–414
Khan SA, Abid M, Hussain F (2015) Nematicidal activity of seaweeds against *Meloidogyne javanica*. Pak J Nematol 33:195–203
Kingman AR, Moore J (1982) Isolation, purification and quantification of several growth regulating substances in *Ascophyllum nodosum* (Phaeophyta). Bot Mar 25:149–154
Kumar NJL, Kumar RN, Patel K, Viyol S, Bhoi R (2009) Nutrient composition and calorific value of some seaweeds from Bet Dwarka, west coast of Gujarat, India. Our Nat 7:18–25
Kumari R, Kaur I, Bhatnagar AK (2011) Effect of aqueous extract of *Sargassum johnstonii* Setchell & Gardner on growth, yield and quality of *Lycopersicon esculentum* Mill. J Appl Phycol 23:623–633
Kumari R, Kaur I, Bhatnagar AK (2013) Enhancing soil health and productivity of *Lycopersicon esculentum* Mill. using *Sargassum johnstonii* Setchell & Gardner as a soil conditioner and fertilizer. J Appl Phycol 25:1225–1235
Latique S, Chernane H, El Kaoua M (2014) Seaweed liquid fertilizer effect on physiological and biochemical parameters of bean plant (*Phaesolus vulgaris* var. *Paulista*) under hydroponic system. Eur Sci J 9:174–191
MacArtain P, Gill CIR, Brooks M, Campbell R, Rowland I (2007) Nutritional value of edible seaweeds. Nutr Rev 65(12):535–543
Manaf HH (2016) Beneficial effects of exogenous selenium, glycine betaine and seaweed extract on salt stressed cowpea plant. Ann Agric Sci 61:41–48
Manivannan K, Karthikai Devi G, Thirumaran G, Anantharaman P (2008) Mineral composition of macroalge from Mandapam coastal region, southeast coast of India. Am-Euras J Bot 1:58–67
Mathur C, Rai S, Sase N, Krish S, Jayasri MA (2015) *Enteromorpha intestinalis* derived seaweed liquid fertilizers as prospective biostimulant for *Glycine max*. Braz Arch Biol Technol 58:813–820
Michalak I, Chojnacka K (2015) Algae as production systems of bioactive compounds. Eng Life Sci 15:160–176
Miller J, Wood JM (1996) Osmoadaptation by rhizosphere bacteria. Annu Rev Microbiol 50:101–136
Milton RF (1952) Improvements in or relating to horticultural and agricultural fertilizers. Br Patent 664:989
Mirparsa T, Ganjali HR, Dahmardeh M (2016) The effect of biofertilizers on yield and yield components of sunflower oil seed and nut. Int J Agric Biosci 5:46–49
Mohammadi M, Tajik H, Hajeb P (2013) Nutritional composition of seaweeds from the Northern Persian Gulf. Iran J Fish Sci 12:232–240
Mohy El-Din SM (2015) Utilization of seaweed extracts as bio-fertilizers to stimulate the growth of wheat seedlings. Egypt J Exp Biol 11(1):31–39
Mounir M, Halima C, Salma L, Abdelali B, Driss H, Mimoun EK (2015) Seaweed extract effect on water deficit and antioxidative mechanisms in bean plants (*Phaseolus vulgaris* L.). J App Phys 27(4):1689–1698

Murata M, Nakazoe J (2001) Production and use of marine algae in Japan. Jpn Agric Res Q 35:281–290

Myklestad S (1964) Experiments with seaweed as supplemental fertilizer. In: Proceedings of fourth international seaweed symposium, Barritz, Pergamon Press, Oxford, pp 432–438

Nabti E, Sahnoune M, Adjrad S, Van Dommelen A, Ghoul M, Schmid M, Hartmann A (2007) A halophilic and osmotolerant *Azospirillum brasilense* strain from Algerian soil restores wheat growth under saline conditions. Eng Life Sci 7:354–360

Nabti E, Sahnoune M, Ghoul M, Fischer D, Hofmann A, Rothballer M, Schmid M, Hartmann M (2010) Restoration of growth of durum wheat (*Triticum durum* var. *waha*) under saline conditions due to inoculation with the rhizosphere bacterium *Azospirillum brasilense* NH and extracts of the marine alga *Ulva lactuca*. J Plant Growth Regul 29:6–22

Nedzarek A, Rakusa-Suszczewski S (2004) Decomposition of macroalgae and the release of nutrients into Admiralty Bay, King George Island, Antarctica. Polar Biosci 17:26–35

Nelson WR, Van Staden J (1984) The effect of seaweed concentrate on wheat culms. J Plant Physiol 115:433–437

Nelson WR, Van Staden J (1985) 1-aminocyclopropane-1-carboxylic acid in seaweed concentrate. Bot Mar 28:415–417

Ozdemir G, Karabay NU, Dalay MC, Pazarbasi B (2004) Antibacterial activity of volatile component and various extracts of *Spirulina platensis*. Phytother Res 18:754–757

Pacholczak A, Nowakowska K, Pietkiewicz S (2016a) The effects of synthetic auxin and a seaweed-based biostimulator on physiological aspects of rhizogenesis in ninebark stem cuttings. Not Bot Horti Agrobo 44:85–91

Pacholczak A, Szydlo W, Jacygrad E, Federowicz M (2016b) Effect of auxins and the biostimulator algaminoplant on rhizogenesis in stem cuttings of two dogwood cultivars (cornus alba 'AUREA' and 'Elegantissima'). Acta Sci Pol Hortorum Cultus 11:93–103

Partani T (2013) Determination of the effect rates of seaweed extract on growth and performance of corn (Sc704) in Gorgan. Int J Agric Crop Sci 6:219–224

Paulert R, Talamini V, Cassolato JEF, Duarte MER, Noseda MD, Smania AJ, Stadnik MJ (2009) Effects of sulfated polysaccharide and alcoholoic extracts from green seaweed *Ulva fasciata* on anthracnose severity and growth of common bean (*Phaseolus vulgaris* L.). J Plant Dis Prot 6:263–270

Peres JCF, De Carvalho LR, Gonçalez E, Berian LOS, D'arc Felicio J (2012) Evaluation of antifungal activity of seaweed extracts. Ciênc Agrotec Lavras 36:294–299

Perez J, Falque E, Domınguez H (2016) Antimicrobial action of compounds from marine seaweed. Mar Drugs 14:1–38

Popescu GC, Popescu M (2014) Effect of the brown alga *Ascophyllum nodosum* as biofertilizer on vegetative growth in grapevine (*Vitis vinifera* L.). Curr Trends Nat Sci 3(6):61–67

Qasmi R (1991) Amino acid composition of some common seaweeds. Pak J Pharm Sci 4:49–54

Rahman MS, Sathasivam KV (2015) Heavy metal adsorption onto *Kappaphycus* sp from aqueous solutions: the use of error functions for validation of isotherm and kinetics models. Biomed Res Int 126298, 1–13

Rajasulochana N, Josmin LL, Leelavathy A (2008) Effect of *Ulva lactuca* extract on the growth of *Phaseolus mungo* L., *Brassica juncea* Hook. F. and Thomas and *Trigonella foenum graceum* L. Indian Hydro 11(2):275–279

Rama Rao K (1991) Effect of seaweed extract on *Zizyphus mauritiana* Lamk. J Indian Bot Soc 71:19–21

Rama Rao (1992) Seaweeds as biofertilizers in India horticulture. Seaw Res Util 14:99–101

Ramarajan S, Henry JL, Saravana GA (2013) Effect of seaweed extracts mediated changes in leaf area and pigment concentration in soybean under salt stress condition. RRJoLS 3:17–21

Rao GMN, Chatterjee R (2014) Effect of seaweed liquid fertilizer from *Gracilaria textorii* and *Hypnea musciformis* on seed germination and productivity of some vegetable crops. Univ J Plant Sci 2(7):115–120

Rayorath P, Khan K, Ravishankar P, Shawna LM, Roumiana S, Simon DH, Alan TC, Balakrishan P (2008a) Extract of the brown seaweed *Ascophyllum nodosum* induce gibberellic acid (GA3)-independent amylase activity in barley. J Plant Growth Regul 27:370–379

Rayorath P, Mundaya NJ, Amir F, Khan W, Ravishankar P, Simon DH, Alan TC, Balakrishan P (2008b) Rapid bioassays to evaluate the plant growth promoting activity of *Ascophyllum nodosum* (L.) Le Jol. using a model plant, *Arabiodopsis thaliana* (L.) Heynh. J Appl Phycol 20:423–429

Reddy AS, Rao PV, Sateesh BJ, Ramana MV (2016) Impact of seaweed liquid fertilizers on productivity of blackgram [*Vigna mungo* (L.) Hepper]. Int J Curr Res Biosci Plant Biol 3:88–92

Reitz SR, Trumble JT (1996) Effects of cytokinin-containing seaweed extract on *Phasealus lunatus* L.: influence of nutrient availability and apex removal. Bot Mar 39:33–38

Renuka Bai N, Banu LNR, Prakash JW, Goldi SJ (2007) Effects of *Asparagopsis taxiformis* extract on the growth and yield of *Phaseolus aureus*. J Basic Appl Biol 1:6–11

Rezaei MA, Kaviani B, Jahanshahi H (2012) Application of exogenous glycine betaine on some growth traits of soybean (*Glycine max* L.) drought stress conditions. Sci Res Essays 7:432–436

Rinku VP, Pandya KY, Jasrai RT, Nayana B (2017) Effect of hydropriming and biopriming on seed germination of brinjal and tomato seed. Res J Agric For Sci 5(6):1–14

Roj E, Dobrzynska-Inger A, Kostrzewa D, Kołodziejczyk K, Sojka M, Krol B, Miszczak A, Markowski J (2009) Extraction of berry seed oils with supercritical CO2. Przemysł Chemiczny 88:1325–1330

Rosalba Mireya Hernández-Herrera FS-R, Ruiz-López MA, Norrie J, Hernández-Carmona G (2014) Effect of liquid seaweed extracts on growth of tomato seedlings (*Solanum lycopersicum* L.). J Appl Phys 26(1):619–628

Russo RO, Berlyn GP (1990) The use of organic biostimulants to help low input sustainable agriculture. J Sustain Agric 1:19–38

Safinaz AF, Ragaa AH (2013) Effect of some red marine algae as biofertilizers on growth of maize (*Zea mayz* L.) plants. Int Food Res J 20(4):1629–1632

Sarin MN, Narayanan A (1968) Effects of soil salinity and growth regulators on germination and seedling metabolism of wheat. Physiol Plant 21:1201–1209

Sasikumar K, Govindan T, Anuradha C (2011) Effect of seaweed liquid fertilizer of *Dictyota dichomata* on growth and yield of *Abelomoschus esulentus* (L.). Eur J Exp Biol 1:223–227

Sekar R, Thangaraju N, Rengasamy R (1995) Effect of liquid seaweed fertilizer from *Ulva lactuca* L on *Vigna unguiculata* L (WALP). Phykos 34:49–53

Selvaraj R, Selvi M, Shakila P (2004) Effect of seaweed liquid fertilizer on *Abelmoschus esculentus* (L). Moench and *Lycopersicon lycopersicum* Mill. Seaweed Res Util 26:121–123

Sethi P (2012) Biochemical composition of the marine brown algae *Pedina terastromatica* Hauck. Int J Curr Pharm Res 4:117–118

Shahbazi F, Nejad SM, Salimi A, Gilani A (2015) Effect of seaweed extracts on the growth and biochemical constituents of wheat. Int J Agric Crop Sci 8:283–287

Sharma AD, Thakur M, Rana M, Singh K (2004) Effect of plant growth hormones and abiotic stresses on germination, growth and phosphatase activities in *Sorghum bicolor* (L.) Moench seeds. Afr J Biotechnol 3:308–312

Sharma RC, Gupta NK, Gupta S, Hasegawa H (2005) Effect of NaCl salinity on photosynthetic rate, transpiration rate, and oxidative stress tolerance in contrasting wheat genotype. Photosynthesis 43:609–613

Sharma SHS, Fleming C, Selby C, Rao JR, Martin T (2014) Plant biostimulants: a review on the processing of macroalgae and use of extracts for crop management to reduce abiotic and biotic stresses. J Appl Phycol 26:465–490

Shevchenko NM, Anastyuk SD, Gerasimenko NI, Dmitrenok PS, Isakov VV, Zvyagintseva TN (2007) Polysaccharide and lipid composition of the brown seaweed *Laminaria gurjanovae*. Russ J Bioorg Chem 33:88–98

Shri Devi SDK, Paul JP (2014) Influence of seaweed liquid fertilizer of *Gracilaria dura* (ag) jag (red seaweed) on *Vigna radiata* (L) R wilczek, in Thoothukudi, Tamil Nadu, India. World J Pharm Res 3:968–978

Singh RP, Kumari P, Reddy CR (2015a) Antimicrobial compounds from seaweed-associated bacteria and fungi. Appl Microbiol Biotechnol 99:1571–1586

Singh SK, Thakur R, Singh MK, Singh CS, Pal SK (2015b) Effect of fertilizer level and seaweed sap on productivity and profitability of rice (*Oryza sativa*). Indian J Agron 60:420–425

Singh S, Singh MK, Pal SK, Trivedi K, Yesuraj D, Singh CS, Anand VKG, Chandramohan M, Patidar R, Kubavat D, Zodape ST, Ghosh A (2016) Sustainable enhancement in yield and quality of rain-fed maize through *Gracilaria edulis* and *Kappaphycus alvarezii* seaweed sap. J Appl Phycol 28:2099–2112

Sivasangari Ramya S, Vijayanand N, Rathinavel S (2015) Foliar application of liquid biofertilizer of brown alga *Stoehospermum marginatum* on growth, biochemical and yield of *Solanum melongena*. Int J Recycl Org Waste Agric 4(3):167–173

Sridhar S, Rengasamy R (2002) Effect of seaweed liquid fertilizer obtained from *Ulva lactuca* on the biomass, pigments and protein content of *Spirulina platensis*. Seaw Res Util 24:145–149

Sridhar S, Rengasamy R (2010a) Significance of seaweed liquid fertilizers for minimizing chemical fertilizers and improving yield of *Arachis hypogaea* under field trial. Rec Res Sci Technol 2:73–80

Sridhar S, Rengasamy R (2010b) Effect of seaweed liquid fertilizer on the growth, biochemical constituents and yield of *Tagetes erecta* under field trials. J Phytol 2:61–68

Sridhar S, Rengasmay R (2011) Potential of seaweed liquid fertilizers (SLFS) on some agricultural crops with special references to profile of seedlings. Int J Dev Res 1:55–57

Srijaya TC, Pradeep PJ, Chtterji A (2010) Effect of seaweed extract as an organic fertilizer on the growth enhancement of black mustard plant. J Coast Environ 1:137–150

Staden JV, Upfold SJ, Drewes FE (1994) Effect of seaweed concentrate on growth of the marigold Tagetes patula. J Appl Phycol 6:427–428

Stephenson WM (1966) The effect of hydrolysed seaweed on certain plant pests and diseases. In: Proceedings of fifth international seaweed symposium, Halifax. Pregamon Press, Oxford, pp 405–415

Sudharsan S, Seedevi P, Ramasamy P, Subhapradha N, Vairamani S, Shanmugam A (2012) Heavy metal accumulation in seaweeds and sea grasses along southeast coast of India. J Chem Pharm Res 4(9):4240–4244

Sultana V, Ehteshamul-Haque S, Ara J, Athar M (2005) Comparative efficacy of brown, green and red seaweeds in the control of root infecting fungi and okra. Int J Environ Sci Technol 2:129–132

Summers PS, Nolte KD, Cooper AJL, Borgeas H, Leustek T, Rhodes D, Hanson AD (1998) Identification and stereospecificity of the first three enzymes of 3-dimethylsulfoniopropionate in a chlorophyte alga. Plant Physiol 116:369–378

Sun TP, Gubler F (2004) Molecular mechanism of gibberellins signaling in plants. Ann Rev Plant Physiol Plant Mol Biol 55:197–223

Sunarpi AJ, Rina K, Nur IJ, Aluh N (2010) Effect of seaweed extracts on growth and yield of rice plants. Bioscience 2:73–77

Sutharsan S, Nishanthi S, Srikrishnah S (2014) Effects of foliar application of seaweed (*Sargassum crassifolium*) liquid extract on the performance of *Lycopersicon esculentum* Mill. in sandy regosol of Batticaloa district Sri Lanka. Am-Eur J Agric Environ Sci 14(12):1386–1396

Tamilselvan N, Hemachandran J, Thirumalai T, Sharma CV, Kannabiran K, David E (2013) Biosorption of heavy metals from aqueous solution by *Gracilaria corticata varcartecala* and *Grateloupia lithophila*. J Coast Life Med 1:102–107

Tarakhovskaya ER, Maslov YI, Shishova MF (2007) Phytohormones in algae. Russ J Plant Physiol 54:186–194

Taskin E, Ozturk M, Taskin E, Kurt O (2007) Antibacterial activities of some marine algae from the Aegean Sea (Turkey). Afr J Biotechnol 6:2746–2751

Tay SAB, Palni LMS, McLeod JK (1987) Identification of cytokinin glucosides in a seaweed extract. J Plant Growth Regul 5:133–138

Temple WD, Bomke AA (1988) Effects of kelp (*Macrocystis integrifolia*) on soil chemical properties and crop response. Plant Soil 105:213–222

Thinakaran T, Sivakumar K (2013) Antifungal activity of certain seaweeds from Puthumadam coast. Int J Res Rev Pharm Appl Sci 3:341–350

Thirumaran G, Arumugam M, Arumugam R, Anantharaman P (2009) Effect of seaweed liquid fertilizer on growth and pigment concentration of *Abelmoschus esculentus* (I) Medikus. Am-Euras J Agron 2:57–66

Thivy F (1964) Seaweed manure for perfect soil and smiling field. Salt Restaur Ind 1:1–4

Tilak KVBR, Ranganayaki N, Pal KK, De R, Saxena AK, Nautiyal CS, Mittal S, Tripathi AK, Johri BN (2005) Diversity of plant growth and soil health supporting bacteria. Curr Sci India 89:136–150

Tuhy Ł, Samoraj M, Basadynska S, Chojnacka K (2015) New micronutrient fertilizer biocomponents based on seaweed biomass. Pol J Environ Stud 24:2213–2221

Van Alstyne KL, Pelletreau KN, Rosari K (2003) The effects of salinity on dimethylsulfoniopropionate production in the green alga *Ulva fenestrate* Postels and Ruprecht (Chlorophyta). Bot Mar 46:350–356

Van Bergeijk SA, Schonefeldt K, Stal LJ, Huisman J (2002) Production and consumption of dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP) in a diatom-dominated intertidal sediment. Mar Ecol Prog 231:37–46

Venkataraman K, Mohan VR, Murugeswari R, Muthusamy M (1993) Effect of crude and commercial seaweed extract on seed germination and seedling growth in greengram and blackgram. Seaw Res Util 16:23–27

Vieira RHSF, Volesky B (2000) Biosorption: a solution to pollution. Int Microbiol 3:17–24

Vinoj Kumar V, Kaladharan P (2006) Biosorption of metals from contaminated water using seaweed. Curr Sci 90:1263–1267

Wally OS, Critchley AT, Hiltz D, Craigie JS, Han X, Zaharia LI, Abrams SR, Prithiviraj B (2012) Regulation of phytohormone biosynthesis and accumulation in Arabidopsis following treatment with commercial extract from the marine macroalga *Ascophyllum nodosum*. J Plant Growth Regul 32:324–339

Washington WS, Engleitner S, Boontjes G, Shanmuganathan N (1999) Effect of fungicides, seaweed extracts, tea tree oil, and fungal agents on fruit rot and yield in strawberry. Aust J Exp Agric 39:487–494

Watee S, Pimonsri M, Onnicha R, Nutapong B, Preeyanuch B (2015) Antimicrobial activity of seaweed extracts from Pattani, southeast coast of Thailand. FABJ 3:39–49

Wosnitza TMA, Barrantes JG (2003) Utilization of seaweed Ulva sp. in Paracas Bay (Peru): experimenting with compost. J Appl Phycol 18:27–31

Younes F, Etahiri S, Assobhei O (2009) Activite antimicrobienne des algues marines de la lagne d'Oualidia (Maroc): criblage et optimization de la periode de la recolte. J Appl Biosci 24:1543–1552

Zbakh H, Chiheb H, Bouziane H, Sa'nchez VM, Riadi H (2012) Antibacterial activity of benthic marine algal extracts from the Mediterranean coast of Morocco. J Microbiol Biotechnol Food Sci 2:219–228

Zhang X, Ervin EH (2008) Impact of seaweed extract-based cytokinins and zeatin riboside on creeping bentgrass heat tolerance. Crop Sci 48:364–370

Zodape ST (2001) Seaweeds as a biofertilizer. J Sci Ind Res 60:378–382

Zodape ST, Kawarkhe VJ, Patolia JS, Warade AD (2008) Effect of liquid seaweed fertilizer and quality of okra (*Abelmoschus esculentus* L). J Sci Ind Res 67:1115–1117

Zodape ST, Soumit M, Eswaran K, Reddy MP, Chikara J (2010) Enhanced yield and nutritional quality in green gram (*Phaseolus radiate* L) treated with seaweed (*Kappaphycus alvarezii*) extract. J Sci Ind Res 69:468–471

Zodape ST, Abha G, Bhandari SC, Rawat US, Chaudhary DR, Eswaran K, Chikara J (2011) Foliar application of seaweed sap as biostimulant for enhancement of yield and quality of tomato (*Lycopersicon esculentum* Mill.). J Sci Ind Res 219:215–219

Integrated Soil Fertility Management Options for Sustainable Intensification in Maize-Based Farming Systems in Ghana

14

Samuel Adjei-Nsiah

Abstract

Declining soil fertility has become a major constraint affecting agricultural productivity in sub-Saharan Africa. Since 2000, several ISFM technologies have been introduced in SSA to address widespread soil degradation on the continent. While studies have shown that ISFM could contribute to increasing agricultural productivity in SSA, several institutional constraints continue to limit its use in the region. In this chapter we have shown how ISFM could contribute to increasing the productivity and profitability of agricultural production in maize-based farming systems in Ghana. We conclude with suggestions to design intercropping research involving grain legumes and cereals to optimise the system in terms of resource use and yield by exploiting legume genotypes that are high yielding and well adapted to intercropping systems.

Keywords

Agricultural productivity · Grain legumes · Mineral fertilizer · Organic resources · Technology

14.1 Introduction

Recent United Nation projections indicate that the world's population will hit 9.7 billion in 2050 (UN 2015). This requires increase in agricultural production to meet the demand for food, feed and fiber. In sub-Saharan Africa where most of the increase in population would occur, agriculture out-put would need to more than double by 2050 to meet increased demand for food, feed and fiber (FAO 2017).

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Agriculture in sub-Saharan Africa (SSA) is however, mostly rain-fed and managed mainly by smallholders making it most vulnerable to climatic variability. Although over 80% of the population in the region directly depend on agriculture (World Bank 2008), SSA still rely on food imports to feed its people (Tadele 2017). In 2013 alone, 56.5 million tons of cereals (maize and wheat) and soybean, worth 18.8 billion USD were imported into the continent (Tadele 2017).

Yields of cereals in SSA are extremely low, averaging about 1.6 tons ha^{-1} compared to the global value of 3.9 tons ha^{-1} (Tadele 2017). This has been blamed on several factors including declining soil fertility, low use and limited access to mineral fertilizer and other improved production technologies (IFDC 2007; Tadele 2017) resulting in hunger, malnutrition and food insecurity. Mineral fertilizer use in sub-Saharan Africa is the lowest in the world averaging 8–10 kg ha^{-1} (IFPRI 2000). Use of mineral fertilizers in SSA is constrained by several factors including risks associated with rainfall variability, high cost and poor access and poor producer price (IFPRI 2000; Morris et al. 2007).

African smallholder farming systems are characterized by low-input agriculture that relies on the inherent organic matter content of the soil to sustain production (IFPRI 2000). While SOM can help in the maintenance of soil fertility by enhancing retention of soil nutrients and water-holding capacity of the soil, continuous cropping and soil erosion could reduce the level of organic matter in the soil thereby causing rapid decline in soil fertility.

Major effects of declining soil fertility include low crop yields, loss of agro-biodiversity, low water use efficiency in cropping systems and soil loss (Mapfumo et al. 2013). Farmers often respond to declining soil fertility and low crop yields through extensification, expanding their agricultural activities to non-agricultural lands. Thus, agricultural productivity in SSA cannot be achieved without soil fertility improvement (Morris et al. 2007).

In the 1960s and 1970s mineral fertilizers were promoted in SSA to increase agricultural production with the thinking that mineral fertilizer alone was sufficient to improve and sustain yields with organic resources playing a minimal role (Fairhurst 2012). The promotion of mineral fertilizers became the main thrust of extension advice from the 1960s onward with most donors and international development organizations playing a key role in promoting mineral fertilizer use (Hilhorst and Toulmin 2000). In the 1980s, use of organic resources was promoted (Vanlauwe et al. 2017) due to limited access to mineral fertilizers because of the structural adjustment program (SAP) and the removal of fertilizer subsidies in much of SSA. However, despite the huge investment made in the promotion of use of organic resources, particularly, green manure and legume trees, for soil fertility improvement, uptake has been very disappointing due to the initial investment needed to establish and plough back the material into the soil. From the 1990s onwards, combined use of mineral fertilizer and organic resources was promoted until 2000 onwards when it was widely recognized that significant improvement in soil fertility cannot be attained without combined use of mineral fertilizers and organic nutrient resources in the form of integrated soil fertility management (ISFM) (Vanlauwe et al. 2010; Bationo et al. 2011; Mapfumo 2011).

Since 2000, several ISFM technologies have been introduced in SSA to address widespread soil degradation on the continent. Studies have shown that ISFM could contribute to increasing agricultural productivity in SSA. This chapter focuses on how ISFM could make different contributions to increasing the productivity and profitability of agricultural production in maize-based farming systems in Ghana. We will first discuss the principles of ISFM. This will be followed by discussions on recent studies in ISFM in the Maize-based farming systems in Ghana and the optimal conditions necessary for uptake of ISFM technologies. We will conclude this chapter with further areas of ISFM research in Ghana.

14.2 Principles of Integrated Soil Fertility Management

Integrated soil fertility management is a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop production (Vanlauwe et al. 2010, 2015). ISFM is based on three principles, namely combined application of fertilizer and organic resources; integration of improved germplasm for any improved strategy for nutrient management and good agronomic practices. According to Fairhurst (2012), these principles recognize that:

1. Neither practices based solely on mineral fertilizer nor soil organic resources are sufficient to sustain agricultural production
2. Well adapted, disease and/or pest resistant germplasm is necessary to make efficient use of available nutrients and
3. Good agronomic practices in terms of planting dates, planting densities and weeding are necessary to ensure efficient use of scarce nutrient resources.

The contributions of the various components that constitute ISFM to crop productivity have been discussed by Fairhurst (2012). According to Fairhurst (2012), organic resources (crop residues and animal manure) constitute an important source of nutrients in crop production. However, while the nitrogen (N), phosphorus (P), magnesium (Mg) and calcium (Ca) content of organic resources is only released and made available for crop use upon decomposition, potassium is often released rapidly because it is released from the cell sap. Moreover, the amount of nutrients contained in organic inputs is usually not sufficient to sustain the required level of crop productivity and obtain the full economic potential of a farmer's production resources. However, besides supplying nutrients, organic resources also contribute to crop growth in several ways including:

- Improving the crop response to mineral fertilizer;
- Enhancing moisture retention capacity of the soil;

- Regulating soil chemical and physical properties that affect nutrient storage and availability;
- Supplying other nutrients not contained in mineral fertilizers;
- Creating a favourable rooting environment
- Improving the availability of P and N for plant uptake;
- Ameliorating soil acidity problems and
- Replenishing soil organic matter

Mineral fertilizers are needed to supplement the nutrients recycled or added in the form of crop residues and animal manures. They are concentrated sources of essential nutrients in a form that is readily available for plant uptake. Based on the cost of the nutrients that they contain; mineral fertilizers are often less costly compared with organic inputs. Yet, they are often considered by farmers as being costly due to limited access to credit by smallholder farmers to purchase them.

ISFM places much emphasize on the use of crop planting materials best adapted to a particular farm environment in terms of responsiveness to nutrients, adaptation to the bio-physical environment and resistance to pest and disease. Improved varieties often have a larger harvest Index (HI) and a higher agronomic efficiency compared with the "unimproved varieties". In addition, some improved varieties have an extensive rooting system which enable them to exploit a larger soil volume for uptake of nutrients compared with unimproved varieties.

14.3 Integrated Soil Fertility Management Practices and Agricultural Productivity within the Maize-Based Farming System in Ghana

14.3.1 Maize-Based Farming System Environment in Ghana

The maize-based farming system in Ghana is a traditional farming system of the forest/savanna transitional and the Guinea Savanna zones of Ghana. Much of the maize-based farming system in the forest/savanna transitional zone used to be part of the tree crop farming system while much of the system covering part of the Guinea Savanna zone used to be noted to produce small grains (sorghum and millet) and rice.

The forest/savanna zone of the farming system used to be a major cocoa-growing area in the early 1940s. The presence of abundant natural resources, particularly fertile land and the booming cocoa industry in the area attracted migrant farmers from the northern part of Ghana and southern Burkina Faso into the zone either to cultivate cocoa or work on the cocoa farms as farm laborers. However, the 1982–83 bush fires across Ghana destroyed much of the cocoa farms in the area. An attempt to replant the cocoa in the area failed partly due to the increasing dryness and deforestation in the area. When it became difficult to replant the cocoa, they shifted to the production of food crops as an adaptation strategy (Adjei-Nsiah and Kermah 2012) and selected crops suitable for the new environment (Donatelli et al. 2000). Farmers resorted to the cultivation of maize, yams and cassava.

Much of the maize-based farming system area in the Guinea Savanna zone of Ghana used to be cropped to small grains (sorghum and millet) and rice. However, with the declining soil fertility and introduction of high yielding maize varieties which respond well to mineral fertilizers coupled with changing dietary pattern of the people and commercialization of agriculture, farmers gradually switched from the cultivation of rice and small grains to maize. Besides maize, other important crops grown in this zone include yam, sorghum, groundnut, cowpea and soybean.

The forest/savanna transitional zone of the maize-based farming system has a bimodal rainfall pattern that begins in April and ends in November with peaks in June/July and September/October. The rainy season is followed by a dry season from December to March. The annual rainfall amount is about 1300 mm. The soils in the area are mainly Lixisols and are mostly fragile with shallow and impermeable iron pans (Asiamah et al. 2000).

The Guinea Savanna zone has a unimodal rainfall pattern and occurs between May and October followed by a long dry season between November and April. Total annual rainfall amount is between 900 and 1113 mm. The soils are classified as Savanna Ochrosol and Groundwater Laterites in the interim Ghana Soil Classification System (Adjei-Gyapong and Asiamah 2002) and as Plinthosols according to the World Resource Base (WRB 2015). The soils are inherently low in fertility (Braimoh and Vlek 2004) expressed in low levels of organic carbon (OC), total nitrogen (N) and available phosphorus (P) (Table 14.1).

Soil total N and available P, the most limiting nutrients for both cereal and legume production in both the forest/savanna transitional and Guinea Savanna zones are very low (Table 14.1) and both N and P deficiencies are widespread. Fertilizer application in Ghana is very low averaging 8–10 kg/ha which is one of the lowest in Africa. While farmers may apply mineral fertilizers to maize, other important crops cultivated in the farming system such as legumes (cowpea, groundnut and soybean) and root and tubers (yam and cassava) hardly receive any fertilizer.

14.3.2 Effect of Integrated Soil Fertility Management on Crops Production

Research results in the maize-based farming systems in Ghana have shown the importance of ISFM in crop production (Adjei-Nsiah et al. 2007, 2008a, 2018; Ahiabor et al. 2014). In both the forest/savanna transitional and Guinea Savanna zones, nitrogen appears to be the most limiting nutrients and the use of N fertilizer in combination with organic resources have been found to increase both maize and cassava yields (Adjei-Nsiah et al. 2007, 2008a).

In the forest/savanna zone of Ghana, Adjei-Nsiah et al. (2007) reported that cropping sequences involving Mucuna and maize in which the maize received 60 kg N ha^{-1} resulted in 100% increase in maize grain yield compared with continues maize cropping. In the same trial, when the maize was preceded by pigeonpea,

Table 14.1 Means and ranges of selected physical and chemical properties of soils of the forest/savanna transitional and Guinea Savanna zones of Ghana

Parameter	Range	Mean
Forest/savanna transitional agro-ecological zone (N = 83)		
pH (H_2O 2:1)	5.43–7.54	6.18
Clay (%)	4.88–13.55	9.32
Sand (%)	59.13–87.02	72.06
Silt (%)	5.52–29.86	18.62
Organic carbon (%)	0.35–1.33	0.76
Total *N* (%)	0.03–0.13	0.07
Avail P mg kg^{-1}	2.76–62.73	16.58
Exchangeable cations (me/100 g)		
K	0.07–1.3	0.25
Ca	1.6–6.91	4.26
Mg	0.53–1.97	1.23
Na	0.05–0.52	0.12
ECEC	2.66–9.53	6.07
Guinea Savanna agro-ecological zone (N = 93)		
pH (H_2O 2:1)	6.03–7.33	6.89
Clay (%)	5.34–15.62	10.12
Sand (%)	57.58–84.31	68.4
Silt (%)	8.22–31.92	21.58
Organic carbon (%)	0.28–1.05	0.50
Total *N* (%)	0.02–0.09	0.05
Avail P mg kg^{-1}	0.72–21.85	6.01
Exchangeable cations (me/100 g)		
K	0.06–0.61	0.30
Ca	0.80–9.08	3.60
Mg	0.27–4.27	1.09
Na	0.03–0,31	0.13
ECEC	1.72–13.92	5.28

or cassava and 60 kg N ha^{-1} was applied to the maize, maize yield increased by about 95%. The large increase in yield of maize when rotated with cassava, mucuna or pigeonpea was attributed to the large amount of organic input incorporated in the soil just before planting the maize. The faster decomposition of the biomass and N release was better synchronized with maize demand. In a similar trial in the same location, Mapfumo et al. 2013 also evaluated ISFM technologies involving the application of N fertilizer and different cropping sequences with farmers. The different cropping sequences evaluated resulted in maize yields benefits ranging from 25% to 125%. Yields of maize were higher on plots previously cropped with cowpea, groundnut and pigeonpea compared with the control under continuous maize cropping or bush fallow.

Efficiency of ISFM technologies depends upon choice of crop variety, retention of legume residues, judicious application of mineral fertilizers and targeting fertilizer to specific phases of the rotation. Several studies (Adjei-Nsiah et al. 2008a;

Kanton et al. 2017; Kermah et al. 2018) in the forest/savanna and the Guinea Savanna zones of Ghana have shown yield benefits of legume/maize rotations on maize grain yields in recent times. In the forest/savanna transitional zone of Ghana, Adjei-Nsiah et al. (2008a) reported of significantly higher maize grain yield increases of between 100% and 150% when maize followed erect cowpea varieties and 275% increase when maize followed an indeterminate creeping cowpea variety compared to maize after maize. The erect cowpea varieties recorded N fertilizer equivalent values of between 18 and 23 kg N ha^{-1} while the indeterminate creeping variety recorded N fertilizer equivalent value of 60 kg N ha^{-1}.

In the northern Guinea Savanna zone of Ghana, Horst and Hardter (1994) showed that rotation of maize with cowpea improves yield and nutrient use of maize on an alfisol. In the same location Kanton et al. (2017) reported of yield increases of maize in soybean/maize rotations of between 1% and 46% when maize was preceded by soybean amended with mineral and/or organic fertilizer.

Integrated soil fertility management in grain legumes has also received research attention in the maize-based farming system in northern Ghana in recent times (Ahiabor et al. 2014; Lamptey et al. 2014; Aziz et al. 2016; Adjei-Nsiah et al. 2018). Widespread response of soybean to rhizobium inoculation and phosphorus application has been obtained in northern Ghana.

Several studies (Ahiabor et al. 2014; Lamptey et al. 2014; Adjei-Nsiah et al. 2018) in the Guinea Savanna zone of Ghana have demonstrated that soybean responds better to rhizobium inoculation when it is applied in combination with 30 kg of phosphorus. In the studies by Ahiabor et al. (2014), inoculation of soybean with rhizobium together with the application of 30 kg P ha^{-1} resulted in grain yield increase of about 122% compared with only 22% increase in grain yield with rhizobium inoculation alone. In the same location, Masso et al. (2016) also reported significantly higher yield increase in soybean grain when soybean seeds were inoculated with rhizobium inoculant and received 30 kg P ha^{-1}.

Similar observations have also been made by Adjei-Nsiah et al. (2018) in the Guinea Savanna zone of Ghana and by Ronner et al. (2015) in a similar environment in northern Nigeria. Phosphorus is known to play a major role in N fixation including legume-rhizobia symbiosis (Yacubu et al. 2010) besides its role in stimulating root growth.

14.4 Optimal Conditions for Uptake of ISFM Technologies

Studies in West Africa (Sterk et al. 2013) suggest that increasing the yield of smallholder farmers have limited impact on their livelihoods since they have few opportunities that can be captured through technologies alone. Africa farmers need “enabling conditions” such as functioning input and output market, access to functioning public research and extension service, rural infrastructure such as roads and market, regulatory framework that ensures a level playing field and access to credit (Adjei-Nsiah et al. 2013). Leeuwis and van Den Ban (2004) suggest that availability and/or functioning of institutions such as input system, output market, credit and land tenure should not only be regarded as conditions that enhance or constrain adoption of promising technologies but should also be regarded and treated as an integral component of agricultural innovation.

14.4.1 Investment in Infrastructure

To promote uptake of ISFM technologies, there is the need to provide key public goods such as public agricultural research and extension and road infrastructure. The diverse and complex nature of farming systems in Africa as well as severe biophysical conditions suggest that no single set of ISFM package could be appropriate for all environments (IFPRI 2000). A vibrant research and extension system is therefore vital for knowledge generation and transfer to farmers in diverse and complex environments. Investments in road infrastructure facilitate farmers access to both input and output market and reduce transportation cost.

14.4.2 Land Tenure

Land tenure systems affect investment in soil fertility management in smallholder farms. Studies (Adjei-Nsiah et al. 2004, 2008a) have shown that secure land tenure is an incentive for smallholder farmers to invest in soil fertility management. If farmers do not have secure access to land, they may not be willing to invest in high cost, slow-repayment processes for rebuilding soil capital and reducing soil erosion. In the forest-savanna transitional zone of Ghana and Benin, Saidou et al. (2007) reported that immigrant farmers engaged in non-sustainable soil fertility management practices not because they did not understand soil fertility but because insecure tenure contracts made them reluctant to invest in soil fertility improvement. In the forest/savanna transitional zone, it became necessary to create platform of landowners, immigrant farmers and traditional authorities to negotiate for more secure tenancy contracts (Adjei-Nsiah et al. 2008b). It is therefore important for government in SSA to implement landholding policies that guarantee long-term investment in soil fertility by farmers.

14.4.3 Input and Output Market

Studies have shown that use of inorganic fertilizer and improved germplasm are a prerequisite for maintenance of soil capital and increase in crop productivity. Thus, uptake of ISFM technologies could be hampered by poorly functioning input and output markets. Agricultural inputs such as fertilizers and improved planting materials must be available in local markets at the right time and at affordable prices. Functioning output market is very essential for uptake of ISFM technologies. If farmers cannot sell their produce this will serve as disincentives for them to invest in ISFM. In both Ghana (Adjei-Nsiah 2008a) and Benin (Saidou et al. 2008), ISFM researchers incurred the displeasure of farmers, after farmers could not market their surplus maize they had helped them to produce in the transitional zone of the two countries.

14.4.4 Access to Credit

Access to credit by smallholder farmers is important for uptake of ISFM technologies. If the cost of ISFM recommended input is beyond the reach of farmers, farmers may need credit to procure them. However, most farmers, especially smallholder farmers do not have access to formal credit and therefore cannot afford to buy mineral fertilizers even where it has been proved beyond doubt that it is profitable (Obeng et al. 1990). In most parts of Africa, credit obtained by farmers for their farming activities is from the informal sector with interest rates ranging from 30% to 100%.

Conclusion

This section summarizes the role of ISFM in enhancing the productivity of the maize-based farming system in Ghana. It also summarizes contributions of research in ISFM to sustainable intensification in the maize-based farming system in Ghana. Maize yields in smallholder farming systems hardly exceeds 2 tons per hectare but recent studies in ISFM suggest that integrated management options that integrates organic nutrient resources and inorganic fertilizers in the production of improved maize varieties could increase maize yields to about 3–4 tons per hectare. Research has also demonstrated the contribution of grain legumes in intensifying the production of maize in the maize farming systems of Ghana. Yield increases of between 100% and 275% have been recorded when maize follows cowpea compared with maize after maize.

Research has also demonstrated the contribution of rhizobium inoculation and P fertilizer to grain legume productivity. Yield increases as high as 120% have been obtained with soybean in studies involving the use of rhizobium inoculant and P fertilizer in northern Ghana. While the use of rhizobium inoculant and P fertilizer may be agronomic effective, the use of P may not benefit a large section of the farming community in economic terms due to poor output/input price ratios of some grain legumes. Although ISFM plays important role in the sustainability of the maize-based farming system in Ghana, its uptake could be hampered by several institutional bottlenecks including land tenure, poor infrastructure, limited access to input and out-put market and credit.

Future Trends in ISFM Research

In most parts of the maize-based farming system in Ghana, grain legumes are either rotated or intercropped with cereals (Adjei-Nsiah et al. 2008a; Kermah et al. 2017a, b). However, yields of both legumes and cereals in the intercropped systems are often low (Kermah et al. 2017a, b). Thus, intercropping research involving grain legumes and cereals should be designed to optimise the system in terms of resource use and yield. One of the limitation to the adoption of cereal/maize intercropping is the limited access to high yielding legume varieties that are also well adapted to intercrop conditions (Tetteh et al. 2017). Future studies should exploit grain legume genotypes that are high yielding and well adapted to intercropping systems. Although smallholder farming systems in much of SSA are characterized by wide diversity of farming household and marked soil heterogeneity (Tittonell et al. 2005; Giller et al. 2011), the use of mineral fertilizers in the maize-based farming system in Ghana has been primarily promoted through blanket recommendation of N, P and K. There is also much inter- or intra- farm soil fertility variations that need to be accounted for in the blanket recommendation. There is therefore the need to develop site-specific fertilizer recommendation for the different maize-based farming system areas in Ghana. While N and P deficiencies are widely known to be widespread in the maize-based farming system in Ghana, very little is known about the extent of deficiencies of potassium (K) and secondary (Mg, Mg, S) and micro-nutrients (Zn, Mn, B and Mo) and their requirement for maize production. In soils of limited nutrient reserves, particularly sandy soils, K, Ca, Mg, Zn, Mn, B and Mo have been observed to limit crop growth (Vanlauwe et al. 2015). There is the need to initiate research to support the development of fertilizer blends containing K, Ca, Mg, S and micro-nutrients.

References

Adjei-Gyapong T and Asiamah RD (2002) The interim Ghana soil classification system and its relationship with the World Reference Base for Soil Resources. In: Quatorzième réunion du Sous-Comité ouest et centre africain de corrélation des sols, Abomey, Benin. 9–13 October 2000. World Soil Resources Report No. 98. FAO, Rome, pp 51–76

Adjei-Nsiah S, Kermah M (2012) Climate change and shift in cropping system: from cocoa to maize based cropping system in Wenchi area of Ghana. Br J Environ Clim Change 2(2):137–152

Adjei-Nsiah S, Leeuwis C, Giller KE, Sakyi-Dawson O, Cobbina J, Kuyper TW, Abekoe M, Van Der Werf W (2004) Land tenure and differential soil fertility management among native and migrant farmers in Wench, Ghana: implications for interdisciplinary action research. Netherlands J Agric Sc 52(3/4):331–348

Adjei-Nsiah S, Kuyper TW, Leeuwis C, Abekoe MK, Giller KE (2007) Evaluating sustainable and profitable cropping sequences with cassava and four legume crops: Effects on soil fertility and maize yields in the forest/savannah transitional agro-ecological zone of Ghana. Field Crops Research 103(2):87–97

Adjei-Nsiah S, Kuyper TW, Leeuwis C, Abekoe MK, Cobbina J, Sakyi-Dawson O, Giller KE (2008a) Farmers' agronomic and social evaluation of productivity, yield and N2-fixation in different cowpea varieties and their subsequent effects on a succeeding maize crop. Nutr Cycle Agro-Ecosyst 80:199–209

Adjei-Nsiah S, Leeuwis C, Giller KE, Kuyper TW (2008b) Action research on alternative land tenure arrangements in Wenchi, Ghana: Learning from ambigous social dynamics and self-organized institutional innovation. Agric Hum Values 25:389–403

Adjei-Nsiah S, Adu-Acheampong R, Debrah K, Dembele F, Lassine S, Ouologuem B, Saïdu A, Vissoh P, Zannou E (2013) Defying "the pervasive bias" against the African smallholders: identifying entry points for institutional change. Dev Pract 23(7):843–856

Adjei-Nsiah S, Alabi BU, Ahiakpa JK, Kanampiu F (2018) Response of Grain Legumes to Phosphorus Application in the Guinea Savanna Agro-Ecological Zones of Ghana. Agronomy Journal 110(3):1089

Ahiabor BDK, Lamptey S, Yeboah S, Bahari V (2014) Application of phosphorus fertilizer on soybean (Gycine max L.) inoculated with rhizobium and its economic implication to farmers. Am J Exp Agric 4:1420–1434

Asiamah RD, Fenning JO, Adjei-Gyapong T, Yeboah E, Ampontuah EO, Gaise E (2000) Report on soil characterisation and evaluation at four multiplication sites (Manpong, Wenchi, Asuansi and Kpeve) in Ghana. Technical Report No. 200. Soil Research Institute, Kumasi

Aziz ALA, Ahiabor BDK, Opoku A, Abaidoo RC (2016) Contributions of Rhizobium inoculants and phosphorus fertilizer to biological nitrogen fixation, growth and yields of three soybean varieties on a fluvic luxisol. Am J Exp Agric 10(2):1–11

Bationo A, Waswa B, Okeyo JM, Maina F, Kihara JM (2011) Innovations as key to the green revolution in Africa: exploring the scientific facts. In: Crawford E, Kelly V, Jayne TSJ (eds) Input use and market development in sub-Saharan Africa. Springer, Dordrecht, 1363p

Braimoh AK, Vlek PLG (2004) The impact of land-cover changes on soil properties in northern Ghana. Land Degrad Dev 15:65–74

Donatelli M, Rosenzweig C, Stockle CO, Tubiello FN (2000) Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. Eur J Agron 13:179–189

Fairhurst T (2012) Handbook for integrated soil fertility management. Technical Centre for Agricultural and Rural Cooperation, Wageningen

FAO (2017) The future of food and agriculture: trends and challenges. Available at www.fao.org/3/9-6583e.pdf. Accessed Feb 2017

Giller KE, Tittonell P, Rufino MC, Wijk MTV, Zingore S, Mapfumo P, Adjei-Nsiah S, Herrer M, Chikowo R, Corbeels M, Rowe EC, Baijukya F, Mwijage A, Smith J, Yeboah E, Burg WJVD, Sanogo OM, Misiko M, Ridder ND, Karanja S, Kaizzi C, K'Ungu J, Mwale M, Nwaga D, Pacini C, Vanlauwe B (2011) Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric Syst 104:191–203

Hilhorst T and Toulmin C (2000) Policy and best practices document. Integrated soil fertility management. Dutch Ministry of Foreign Affairs, The Hague, 64pp

Horst WJ, Hardter R (1994) Rotation of maize with cowpea improves yield and nutrient use of maize compared to maize monocropping in an alfisol in the northern Guinea Savanna of Ghana. Plant Soil 160:171–183

IFDC (2007) African fertilizer summit proceedings June 9–13, 2006 Abuja, Nigeria. Special Publication. International Fertilizer Development Centre (IFDC), Muscle Shoals, Alabama, 182pp

IFPRI (2000) Integrated nutrient management, soil fertility and sustainable agriculture: current issues and future challenges. Food, agriculture and the environment discussion paper 32, IFPRI, Washington, DC, USA, 2006

Kanton RAL, Buah SSJ, Larbi A, Mohammed AM, Bidzakin JK, Yakubu E (2017) Soil amendments and rotation effects on soybean and maize growths and soil chemical changes in northern Ghana. Int J Agron. https://doi.org/10.1155/20174270284

Kermah M, Frank AC, Adjei-Nsiah S, Ahiabor BDK, Abaidoo RC, Giller KE (2017a) N_2 fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2017.08.028

Kermah M, Frank AC, Adjei-Nsiah S, Ahiabor BDK, Abaidoo RC, Giller KE (2017b) Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of norther Ghana. Field Crop Res 213:38–50

Kermah M, Franke AC, Ahiabor BDK, Adjei-Nsiah S, Abaidoo RC, Giller KE (2018) Legume-maize rotation or relay? Options for ecological intensification of smallholder farms in the Guinea Savanna of Northern Ghana. Exp Agric, doi: 10.1017/S 00 14479718000273

Lamptey S, Ahiabor BDK, Yeboah S, Asiama C (2014) Response of soybean (Glycine max) to rhizobium inoculation and phosphorus application. J Exp Biol Agric Sci 2(1):72–77

Leeuwis C, Van Den Ban A (2004) Communication for rural innovation: rethinking agricultural extension, 3rd edn. Blackwell Science, Oxford

Mapfumo P (2011) Comparative analysis of the current and potential role of legumes in integrated soil fertility Management in Southern Africa. In: Bationo A, Waswa B, Okeyo JM, Maina F, Kihara J, Mokwunye U (eds) Fighting poverty in sub-Saharan Africa: the multiple roles of legumes in integrated soil fertility management, 1st edn. Springer, New York, pp 175–200

Mapfumo P, Adjei-Nsiah S, Mtambanengwe F, Chikowo R, Giller KE (2013) Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholders in Africa. Environ Dev 5:6–22

Masso C, Mukhongo R, Thuita M, Abaidoo R, Ulzen J, Kariuki G, Kalumuna M (2016) Biological inoculants for sustainable intensification of agriculture in sub-Saharan Africa smallholder farming systems. In: Climate change and multi-dimensional sustainability in African agriculture. Springer, Cham, pp 639–658

Morris M, Kelly VA, Kopicki RJ, Byerlee D (2007) Fertilizer use in African agriculture: lessons learned and good practice guidelines. The World Bank, Washington, DC, 144pp

Obeng HB, Erbyn KG, Asante EO (1990) Fertilizer requirements and use in Ghana. Consultancy Report, Tropical Agricultural Development Consultancy, Accra, Ghana.

Ronner E, Franke AC, Vanlauwe B, Dianda M, Edeh E, Ukem B, Bala A, Van Heerwaarden J, Giller KE (2015) Understanding variability in soybean yield and response to P-fertiliser and rhizobium inoculants on farmers' fields in northern Nigeria. Field Crop Res 186:133–145

Saidou A, Tossou R, Kossou D, Sambieni S, Richards P, Kuyper T (2007) Land tenure and sustainable soil fertility management in central Benin: towards the establishment of a cooperation space among stakeholders. Int J Agric Sustain 5(2&3):195–213

Saidou A, Adjei-Nsiah S, Kossou D, Sakyi-Dawson O, Kuyper TW (2008) Securite fonciere et gestion de la fertilite des sols: etudes de cas au Ghana et au Benin. Cah Agricult 16(5):1–8

Sterk B, Kobina C, Gogan AC, Kossou D, Sakyi-Dawson O (2013) Five years after: the impact of a participatory technology development programme as perceived by smallholders in Benin and Ghana. J Agric Educ Ext 19(4):361–379

Tadele Z (2017) Raising crop productivity in Africa through sustainable intensification. Agronomy. https://doi.org/10.3390/agronomy7010022

Tetteh FM, Quansah GW, Frempong SO, Nurudeen AR, Atakora WK, Opoku G (2017) Optimizing fertilizer use within the context of integrated soil fertility management in Ghana. In: Wortman CS, Sones K (eds) Fertilizer use optimization in sub-Saharan Africa. CABI, Wallingford, pp 67–81

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ 110:166–184

United Nations, Department of Economic and Social Affairs, Population Division (2015) World population prospects. The 2015 revision, key findings and advance tables. Working paper 40. ESA/P/WP 241

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD, Smaling EMA, Woome PL, Sanginga N (2010) Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric 39:17–24

Vanlauwe B, Descheemaeker K, Giller KE, Huising J, Merckx R, Nziguheba G, Wendt J, Zingore S (2015) Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil Discussant 1:1239–1286

Vanlauwe B**,** Abdelgadir AH, Adewopo J, Adjei-Nsiah S, Ampadu-Boakye T, Asare R, et al (2017) Looking back and moving forward: 50 years soil and soil fertility management research in sub-Saharan Africa. Int J Agric Sustain https://doi.org/10.1080/14735903.2017.1393038.

World Bank (2008) World Development Report 2008: Agriculture for development - response from a slow trade - sound farming perspective. The World Bank, Washington DC

WRB (2015) World Reference Base for Soil Resources 2014, update (2015) International soil classifiication system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome

Yacubu H, Kwari JD, Sandabe MK (2010) Effect of phosphorus fertilization on nitrogen fixation by some grain legume varieties in Sudano-Sahelian zone of North Eastern Nigeria. Niger J Basic Appl Sci 18(1):19–26

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The original version of this chapter was inadvertently published without the sources for Tables 6.1, 6.2 and 6.3.

The current version of the chapter had been revised with the following sources added:

Table 6.1 source: Adapted and modified from Khadka et al. (2017)
Table 6.2 source: Adapted and modified from Tripathi and Jones (2010)
Table 6.3 source: Adapted and modified from Tripathi and Jones (2010)

The updated version of this chapter can be found at
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