# Chapter 14
# Non-Judicious Use of Pesticides Indicating Potential Threat to Sustainable Agriculture


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**Abstract** Worldwide, pesticides have proved to be a boon for the farmers by increasing agricultural yield and providing innumerable benefits to society directly and indirectly. For instance, India witnessed the green revolution during the 1960s that redefined the low input to high input more intense agriculture system that contributed to transforming Indian agriculture from food-deficit to food-surplus nation. Nevertheless, the issue of hazards posed by pesticides to human health and the environment cannot be ignored. Non-judicious overuse of pesticides is acting as the source of emerging contaminants in agro-ecosystems. It has been linked to a wide range of human health hazards, ranging from short-term impacts such as headaches and nausea to chronic impacts like cancer, reproductive disorders, and endocrine disruption. Moreover, contamination of air, water and soil that end up adversely affecting the survival of other organisms such as non-targeted plants, birds, and aquatic flora and fauna has also been reported.

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The present study aimed to give a brief history of pesticide use globally, case studies of pesticide use consequences particularly in the Indian context and strategies to mitigate the ill effects. In general, this study also focuses on direct and indirect impacts of pesticide exposure on air quality, water contamination, soil pollution and human health. Besides, we highlighted detailed case studies of over usage of pesticides states of Punjab, Haryana and Kerala in India. In all the case studies, hyper-accumulation of pesticides led to detrimental effects in all age classes of human beings and their surroundings. Integrated pest management (IPM) should be developed and extended, for effective, affordable, and environmentally-sound control strategies for detrimental biotic agents. The integration of pesticides with natural enemies has more significant potential than is utilized at present and it could help to mitigate the negative consequences of pesticide overuse. Judicious use with IPM, ecological engineering and biological control is highly considerable and beneficial in the long term to sustain agriculture productivity without compromising the environment and human health.

**Keywords** Biomagnification · Biopesticides · Cancer · Ecological engineering · Environmental impact · Health impacts · Integrated pest management

## Abbreviations

| | |
|---|---|
| DDT | Dichloro Diphenyl Trichloroethane |
| DNA | Deoxyribonucleic Acid |
| EPA | Environment Protection Agency |
| HCH | Hexachlorocyclohexane |
| HYVP | High Yielding Variety Programme |
| IPM | Integrated Pest Management |
| OCP | Organo-Chlorine Pesticides |
| PPE | Personal Protection Equipment |
| USA | United States of America |
| USGS | United States Geological Survey |
| WHO | World Health Organization |

## 14.1 Introduction

According to the World Health Organization (WHO) each year more than 3,000,000 cases of pesticide poisoning and 22,000 deaths are reported in developing countries (Lah 2011). Moreover, the inefficient and extensive use of pesticides during the last

5 to 6 decades inadvertently has led to the serious deterioration of environmental quality with increased health risks to living organisms, including humans (Khalid et al. 2020). One major challenge encountered globally is emerging contaminants in agriculture mainly due to hasty growth of the pesticide industry that increased the chemical burden on the natural environment in various ways. For instance, about 75% of pesticide use in the USA was in agriculture (Calvert et al. 2008) and in Europe, despite international efforts to promote the sustainable use of pesticides in agriculture. Overall pesticide use did not decline substantially in the WHO European Region during the period of 1990s (Robertson et al. 2004). Worldwide, contamination of soil and water with various types of pesticides, resulting from accidental spills at agrochemical manufacturing, formulation, and distribution facilities, farm loading/wash-down sites, or abandoned waste sites, is a serious environmental problem (Abbas and Al-Madhhachi 2020). Md Meftaul et al. (2020) provides updated knowledge on the sources, nature and extent of pesticide pollution in the urban environment, and the ecological and human health effects of pesticides and their residues that hinders sustainable livelihood. However, the urgent need is to understand and act holistically on emerging contaminants for a more ecological sustainable approach with promising innovative ideas that potentially transforms agriculture and food production systems.

Indian economy chiefly depends on the agriculture sector as it provides employment and livelihood to more than 70% of the population. As per the current trend of population explosion around the globe, it is predictable that India will surpass China and become the most populous nation in the world by 2022 (BBC News Asia 2015). At present, India supports 17.84% (1.32 billion) of the world population, with 2.4% land resource and 4% of water resources (Yadav and Dutta 2019). Vegetables and fruits are considered a healthy choice to fulfill the essential nutritional requirement of the increasing population. There are many reasons for cultivating vegetables as it has good market value, short cultivation time (45–60 days) and a new earning source for farmers. Though fulfilling the nutritional requirements, cultivation of fruits and vegetables heavily rely on use of pesticides for controlling diseases and pests. Pesticides have played an essential role in reducing losses from the weeds, diseases and insect pests that can markedly reduce the amount of loss and increase the profit (Kaur et al. 2019). However, almost 62% of vegetables and 82% of fruits have been found to be contaminated with pesticides (FDA Pesticide monitoring report 2019). According to the Food and Agriculture Organization (2018) "*Pesticides are any substance or blend of substances that diminish the harmful population of pests of bugs.*" According to the United States Environmental Protection Agency (2018) "*Pesticides intend to control pests, as well as weeds and protect plant health from harmful biotic agents*". The pattern of pesticide application in the world and India, are shown in Fig. 14.1. In India, insecticides alone constitute 76% of the total pesticides, whereas this figure is only 44% at the world level (Mathur 1999).

When pesticides are applied, plant tissues absorb them. Not only the absorption but adsorption also takes place (Kaur et al. 2019). Adsorption is the physical binding of pesticide molecules to soil particles or any other surface. The physical and

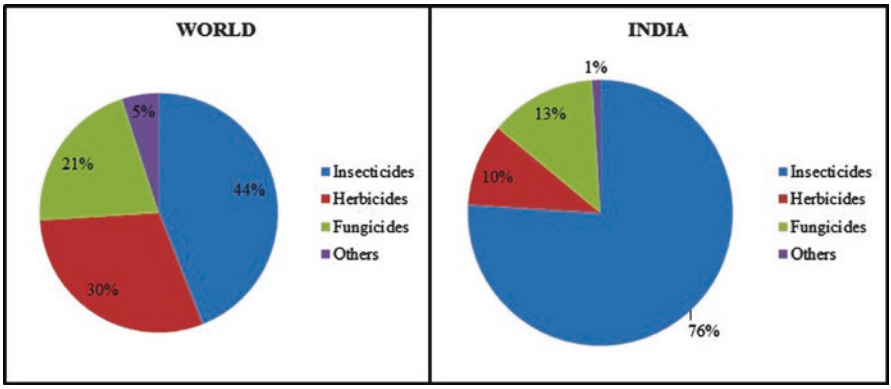


**Fig. 14.1** The categories wise application of pesticides in the world and India during cultivation

chemical properties of pesticides depend on the pH of the soil, its concentration, and the composition of the soil. Some soluble pesticides bind strongly with soil as a soil containing clay has more surface area and high water holding capacity (Das et al. 2019). The more clay particles and organic matter in the soil, the more the pesticide is held by the soil and becomes immobile and unlikely to leach down unless the soil particles to which they were adsorbed move with water (Takeshita et al. 2019). The longer the molecules of a pesticide are held, the more microbiological degradation will occur, which reduces the risk of leaching and erosion. Erosion is the movement of soil particles from the application site by heavy rains or excess irrigation. If the pesticide is not adsorbed to the soil particle, the pesticide is also being moved off-site and may contaminate the groundwater. This chapter highlights pesticide application in global and Indian agriculture and its impact on air, water, soil and human health. The pesticides hazard cases especially from Punjab, Haryana and Kerala states of India have been explored in detail in the present chapter.

## 14.2 Classification of Pesticides

The classification of pesticides, based on their chemical composition and nature of ingredients, is depicted in Fig. 14.2. The classification is based on the efficacy, physical and chemical properties of the respective pesticides (Kaur et al. 2019).

## 14.3 Pathways of Pesticides Contamination

In natural soil conditions, there may be cocktails of pesticides together or other contaminants in addition to pesticides at a time in a particular location. The co-occurrence of different pesticides and other contaminants might have different

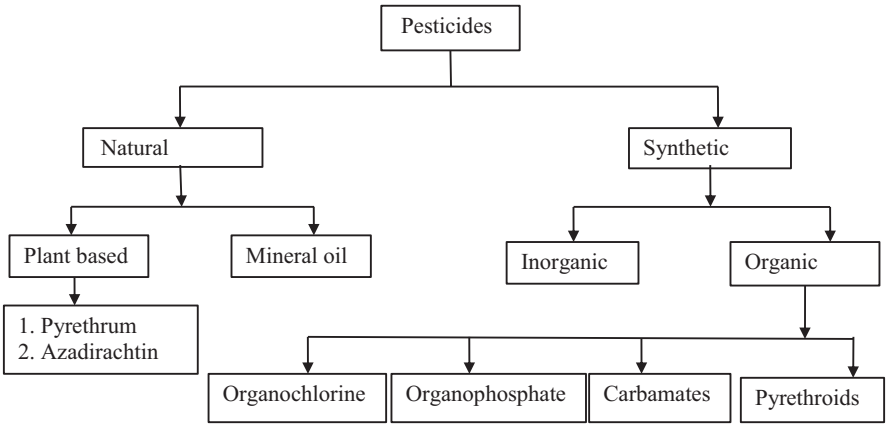


**Fig. 14.2** Demonstration of the classification of the pesticides in natural and synthetic categories, with their principal chemical constitutes

properties and effects on microbial activity, biomass, and diversity. The pesticides application may be harmful to the microbial community, disturb soil ecosystem, and thus, may affect human health by entering in the food chain (Hussain et al. 2009). There are many ways through which pesticides can enter the human body and can cause hazardous effects on human health. For example:

(a) Breathing- Pesticides are present in vapors form that can be easily inhaled during their application time.
(b) Ingestion- Ingestion of these chemicals occurs through crops or through direct accidental ingestion.
(c) Dermal- Absorption through the skin.
(d) Eye exposure- Pesticides can enter through eyes in the human body when these are used in spray form.

Over dose of pesticides act as pollutants and can also enter the food chain through contaminated food and may induce many health hazards (Fig. 14.3). Morphological and biochemical changes in *Vigna radiata* and *Spinacia oleracea* induced by fluoride contamination in soils from various sources were reported by Tyagi et al. (2019). Several studies have reported that in many developing countries including India, the pesticide application is indiscriminate and beyond safe limits (Dey 2016).

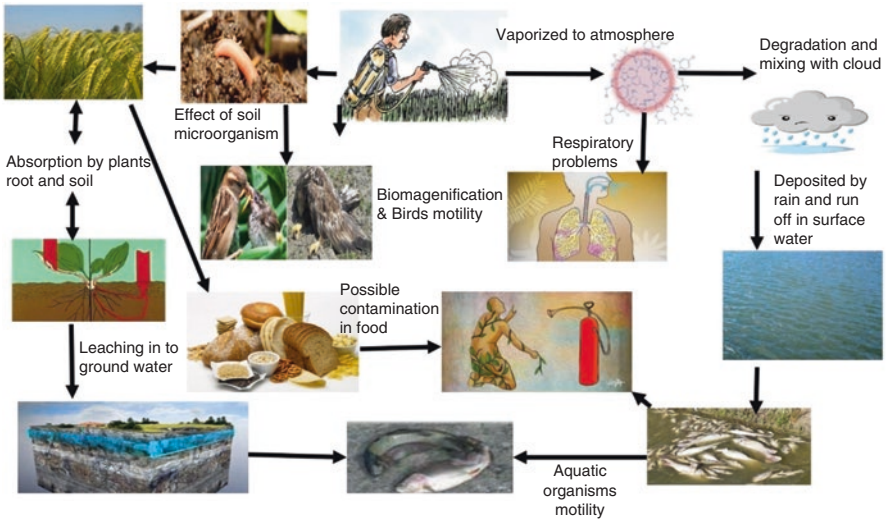


**Fig. 14.3** Pictorial representation of pesticides application on crops and their transmission into atmosphere, terrestrial and aquatic ecosystems to animals and human beings which leads lethal effect both on human and environment through biomagnification, consequently inter- and intra-transmission in different components of ecosystem, human and animal and its harmful effects

## 14.4 Outcomes of Pesticide Application

### *14.4.1 The Global Perspectives*

Globally pesticide consumption has increased drastically for crop/food security to feed the increasing population (Zhang et al. 2011). Total pesticides (tonnes) applied worldwide in agriculture is presented in Fig. 14.4. In history, pesticides may be divided into three phases; the first phase of the pesticide history was before the 1870s in ancient Greece when sulfur was used as natural pesticides to control pests (Zhang et al. 2011). The era of inorganic synthetic pesticides was the second phase (1870s-1945), wherein natural material and inorganic compounds were used for the controlling pests. The third phase which is well known as the era of organic synthetic pesticides started in 1945, in which man made organic pesticides like DDT, 2,4-D, HCH, Dieldrin were used. In the earlier era, only three organically synthesized pesticides viz. Carbamate, Organophosphorus, and Organochlorine were used but after the introduction of herbicides, fungicides, and bactericides significant changes in uses of these pesticides were noticed (Zhang et al. 2011). Pesticides consumption endures substantial changes since the 1960s, it increased from 20% in 1960 to 48% in 2005 (Zhang et al. 2011).

The largest consumer of pesticides is Europe followed by Asia, while China, the US, France, Brazil and Japan are the largest pesticide producers, consumers or traders in the world (Zhang et al. 2011). A portion of the credit of high yields and

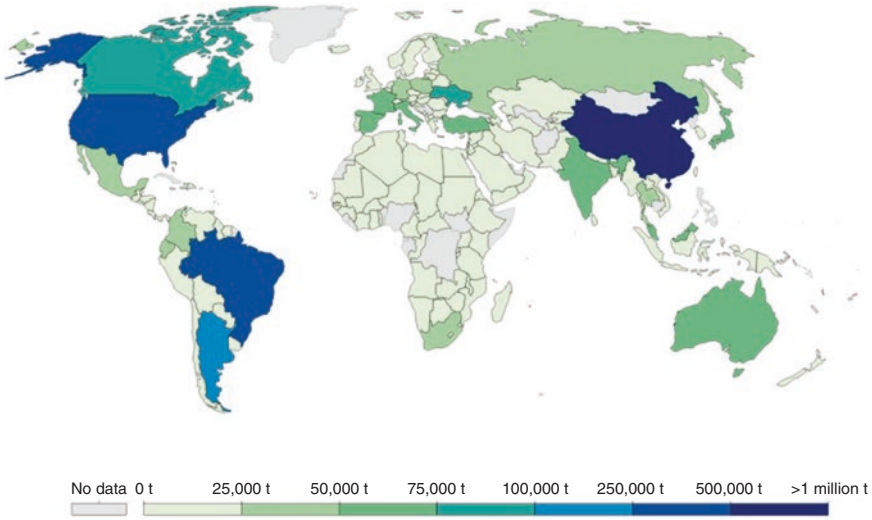


**Fig. 14.4** Details of the total pesticides measured in tones applied in global agriculture. Dark geographical area and light geographic area demonstrates higher and lower measurement of pesticides, respectively (FAO 2017)

production, ensuring food security goes to pesticide application while they have several negative consequences on air, water, and soil by acting as environmental contaminants and causing hazards to human and other life forms exerting toxic effects.

Worldwide approximately 10,000 insects and mite's species, 50,000 plant pathogens species, and 8000 weeds species are documented to damage plant health and hence crop productivity (Dhaliwal et al. 2010). Insect pests cause approximately 14% loss, plant pathogens cause nearly 13% losses, and weeds around 13% loss (Pimentel 2009). In a farmer's perspective, pesticide is crucial for enhancing agricultural production. Studies have even reported that around one-third of the agricultural products are produced by using pesticides (Liu et al. 2002), while without using pesticide, the loss of fruits, vegetables, and cereals due to pest injury would reach 78%, 54%, and 32%, respectively (Cai 2008). The pesticides application significantly reduces 35–42% crop loss due to various pests (Pimentel 1997; Liu and Liu 1999). Because of the world's limited croplands and growing population (Zhang et al. 2006; Zhang 2008), it is necessary to take all measures to increase crop production. Increased pesticides application (average) worldwide was to ensure reduction in a range of pests infesting agricultural crops (Fig. 14.5).

Developing strong consciousness among the policymakers about Integrated pest management (IPM) as an ecosystem-based approach and strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Ecological engineering holistically adopted to increase

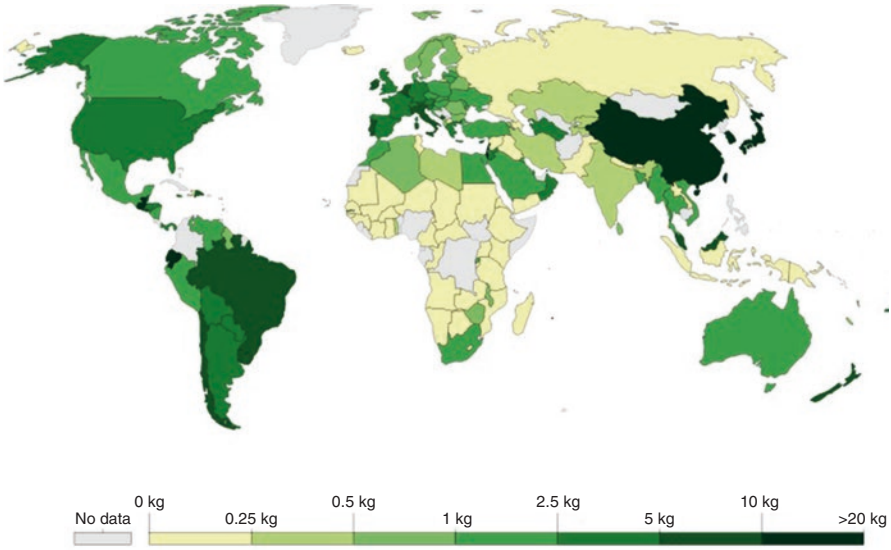


**Fig. 14.5** Details of the average pesticide application per unit of cropland, measured in kilograms per hectare in global agriculture. Dark geographical area and light geographic area demonstrates the higher and lower use of pesticides, respectively (FAO 2017)

natural predators of pests that not only controls pest population but also enhances aesthetic value. In the next section, we focused on pesticide use and ill effects in Indian context with some case studies from different regions of India.

### *14.4.2 The Indian Perspectives*

Pesticide application as a trend started after the green revolution, and since the green revolution, there has been an enormous increase in food grain (Niti.gov.in 2017). It has made a significant contribution in transforming India from food-deficit to food-sufficient nation. To increase agricultural productivity, the Government of India initiated a new 'agriculture strategy', the High-Yielding Varieties Programme (HYVP). This depended crucially on high yielding varieties of seeds, along with regular and adequate irrigation, fertilizers, pesticides, insecticides, and agricultural equipment. However, an enormous amount of contaminant loaded fertilizers and pesticides usage leads to various deformities in bodies, mental problems, hormonal problems, cancer and lots of new types of diseases (Zhang et al. 2011). Despite several achievements, the green revolution has resulted in the above listed effects in India.

In India, pesticide production started in 1950 and now the country has become the 2nd largest producer of pesticide. According to the Directorate of Plant Protection and Quarantine (2011), India grew steadily from 5000 MT in 1959 to 85,000 MT in

2009–2010, which makes it 2% of the total market of the world in revenue generation (Statistical Yearbook of India 2011). Organochlorine dichlorodiphenyltrichloroethane (DDT) was the first agrochemical which was used in India in 1948 as an insecticide (Bhardwaj and Sharma 2013). After the green revolution period, the consumption of pesticides increased from $0.29 \times 10^6$ MGT (1960–61) to $12.15 \times 10^6$ MGT (1992–1993) (Singh 2000). Though, the consumption of pesticides in India is less from other countries like Japan and Germany, non-judicious usage of pesticides in India increased due to poor agricultural management strategies and practices, lack of knowledge about hazardous behaviour of pesticides among farmers. As a tropical country, India differed in the consumption of pesticides from the rest of the world, which skewed toward the usage of insecticides (Indian Pesticides Industry 2011), which account for 76% of total usage. Crop specific consumption of pesticides reveals that cotton accounts for highest consumption followed by paddy at 37% and 20%, respectively. Other crops such as wheat, vegetables, and other plant crops consumed 9%, 2% and 7% of pesticides, respectively (Ministry of Agriculture, Govt. of India 2009). Andhra Pradesh ranked first followed by Punjab and Maharashtra in the consumption of pesticides (Bhardwaj and Sharma 2013).

## 14.5 The Potential Threat of Pesticides in Air, Water and Soil Environment

Excessive dose of agrochemicals (pesticides) with several emerging contaminants affect the air quality, water purity, and soil health by their hazardous transformations (Fig. 14.6). Limited research is available on contamination of air by pesticides

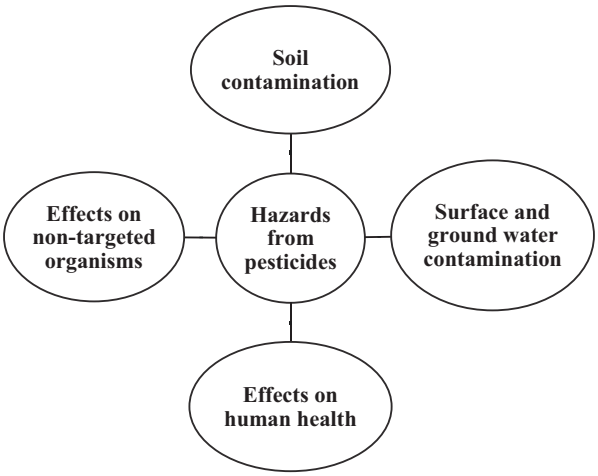


**Fig. 14.6** The hazardous impact of massive use of pesticides on soil, water, air, other living creatures and human health

application than other pollutants. Pesticide sprays may drift and volatilize and can form aerosol in the target area, which can contaminate the ambient air of that area (Socorro et al. 2016). The drift of sprays losses 2–25% of applied agrochemical which can sink into the air and spread >100 miles and 80–90% of applied treatment can volatilize within couple of the day after application and secondary pollutants may be resultant from the same as the precursor (Socorro et al. 2016).

Surface, as well as groundwater contamination, is a worldwide problem due to pesticide application. Such contamination of both surface and groundwater affects aquatic fauna and flora, as well as human health (Cerejeira et al. 2003; Hossain et al. 2015). Aquatic organisms are directly exposed to chemicals resulting from agricultural production via surface run-off or indirectly through trophic chains. Pesticides can reach surface water like river streams etc. by run-off and into groundwater by leaching (Aktar et al. 2009). Pesticides leaching and run-off contribute >50% to the surface water pollution (EPA 2009). According to the United States Geological Survey (USGS), at least 143 different pesticides and 21 transformation products have been found in groundwater (Aktar et al. 2009). Organochlorine Pesticides (OCPs), DDT, Endosulfan, Endrin, Aldrin, Dieldrin, etc. were reported in drinking water supply in Delhi and river Yamuna (Agrawal et al. 2015). Endosulfan and Di-chloro-diphenyl-trichloro-ethane (DDT) detected in Bihar and Uttar Pradesh (Agarwal et al. 2015). Total 58% of samples of drinking water were observed to be contaminated with pesticides in Bhopal, Madhya Pradesh, India (Kole and Bagchi 1995). Eleven states found nitrate contamination in India due to pesticides application (Kumar and Shah 2006).

Excessive application of agrochemicals leads to changes in soil reaction, poor soil fertility, improper nitrogen fixation, changes in biogeochemical cycles, loss in carbon content, etc. problems in agriculture (Aktar et al. 2009; Arya et al. 2018). Exposure to pesticides may affect humans and other life forms as an unwanted side effect to the environment (Igbedioh 1991; Forget et al. 1993). Producer workers, distributors, pest control workers, and farmers may directly or indirectly get affected due to exposure to pesticides. Most of the pesticides may transfer through the food chain by biomagnification from one trophic level to another next trophic level. Pesticides, hazardous in chemical nature like neurotoxins, can affect liver, kidney, and reproductive cycle in humans. Hence, pesticides are toxic, risky and health hazardous to the human being.

## 14.6 Case Studies Related to Pesticide Use

Indiscriminate use of numerous pesticides like insecticides, herbicides/weedicides, fungicides, rodenticides, etc. lead to accumulation of diverse emerging contaminants in the soil-plant-water continuum and adversely affect the environment and human health. All the farmers and communities who are directly or indirectly linked to exposure as well as biomagnification through the food chain have to face the effect and repercussions of using herbicides and pesticides. At that time Punjab state

being a wealthy state, and literacy rate being high, they accepted and adopted the modern technologies of green revolution in 1965 (Luwanda 2018) but in the present scenario it is subjected to the severe repercussions of excessive pesticide use and is worst affected.

In Rangareddy district, Andhra Pradesh, India, a study was conducted by Rao et al. (2009), in 2007 and they found pesticide residues were revealed in the vegetable like okra, tomato, cucumber, brinjal, etc. and also in the collected water samples from Kotapally Adarsha watershed. Approximately, the quantity of chlorpyrifos, cypermethrin and endosulfan was 0.001 to 0.352 mg $kg^{-1}$, 0.001 to 5.154 mg $kg^{-1}$ and 0.001 to 0.784 mg $kg^{-1}$, respectively. Endosulfan residues were found to be below residual limit while chlorpyrifos and cypermethrin residues were above the limit in 59, 4 and 2 samples, respectively. In water samples residues were also found but below the residual limit. This shows that pesticides, whether in high or low concentrations, are always served in plates in the form of vegetables.

Kumari and Sharma (2012) investigated the consequences of pesticide usage on the health of farmers of Kullu and Shimla districts of Himachal Pradesh, India. Interviews of 100 farmers were conducted in each district by using a pre-tested questionnaire. Most of the farmers were directly exposed to pesticides when spray was done by themselves in high-value cash crops. While doing spray, only 22% and 8% of the farmers were using polythene to cover their nose and mouth in Kullu and Shimla, respectively. Personal Protective Equipment (PPE) was not used by farmers while spraying pesticides. The majority of the farmers were not adopting IPM in Kullu (80%) and Shimla (86%). Due to the indiscriminate use of pesticides, farmers suffered from several toxicity related diseases. In Kullu, farmers responded that 86% were suffering from eye irritation, 81% from fatigue, 66% from skin irritation, 59% from back pain and headache, 56% from vomit and 22% from dizziness. While in Shimla, 78% farmers were suffering from the symptoms of eye irritation and back pain followed by fatigue (77%), headache (77%), skin irritation and nausea (41%) and eye flu (31%). 90% of the farmers in Kullu and 62% in Shimla reported that pesticides also killed beneficial insects and bees. This implies that the usage of excessive pesticides without protective measures adversely affect human health and the environment (Kumari and Sharma 2012). Therefore, there is a need to make farmers more aware through authorities responsible regarding the usage of IPM and protective gear, while handling pesticides. The present study compiles the effect of pesticides in four different regions of India.

### *14.6.1 A Case Studies of Punjab, India*

The present case study was an attempt to compile scattered pieces of literature that evidenced the adverse effects of pesticides in Punjab, India. Punjab that witnessed green revolution is now majority ruined because of adoption of massive and non-judicious use of pesticide, herbicide and fertilizer overuse which had weakened the

immunity of local population and made them susceptible to diseases (Mittal et al. 2014).

In Malwa region of Punjab nearly 75% consumption of the pesticide was reported in comparison to the whole state. With an enormous amount of pesticide usage, it is suspected to affect the whole environment such as soil, water and air which ultimately enter the food chain and affect the local population and nearby population. Within two decades, many cases of mental disabilities and reproductive disorders were reported. According to the study of Kumar (2005), 7441 deaths were recorded in the period 1993–2003 because of cancer in Talwandi region and maximum cases were of female reproductive cancer. Out of 11 districts of Malwa region, 4 districts namely Muktsar, Mansa, Bathinda, and Faridkot were reported to be badly affected by cancer cases of various types. In this region, 2 villages Giana and Jajjal of Bathinda district have been declared as "*cancer-stricken villages*" (Thakur et al. 2008) and Malwa region is known as 'Cancer Capital' of India. A passenger train from Bohar to Jodhpur passengers known as 'cancer train' because of approximately 60 cancer patients per day were carried by it to the cancer treatment hospital and research institute in Bikaner, Rajasthan, India. Kaur et al. (2011) studied the DNA of exposed farmers and control (210 samples) which reveals that 1/3rd of the samples was genetically damaged due to pesticide exposure. Thereby, a high risk of DNA damage due to pesticide exposure has been observed. Another study of the past year reported cancer and other life-threatening ailments due to contaminated drinking water with heavy metals and pesticides (Thakur et al. 2008).

### *14.6.2 A Case Study from Faridabad, Haryana, India*

Study revealed that continuous and long-term exposure of chemical pesticides in various forms and conditions leads to chronic health effects which were admitted by the respondents. The most common symptoms observed in respondents were headache and dizziness (27%), followed by eye problems like itching and redness (23%). Other most widespread problems were allergy to hands, face, neck, feet, and skin of other exposed body parts (18%), and vomiting and nausea (16%). More than 11% of farmers also reported diarrhea and stomach-ache. Serious health problems such as asthma, migraine, development of permanent skin patches, etc. were found in almost 16% of farm workers (Tyagi et al. 2015). Knowledge dissemination, awareness campaign and provision of alternatives to fares are the key to reduce ill effects of pesticide to human health.

### *14.6.3 A Case Study from Kasaragod, Kerala, India*

Kasaragod tragedy due to Endosulfan aerial spraying is well known after the episode of 'Satyamev Jayate' where they publicise the hazardous after effects of pesticide usage. There, aerial spraying of Endosulfan was started on cashew cropland continuously for 20 years (Venugopal 2008). Effects of such exposure were revealed when cases of mental disorder, chemical neurotoxicity, physical deformities, reproductive failure, and delayed sexual maturity came into front very often. One out of five houses was affected by any one of the above problems due to pesticide exposure. In 2011, the Supreme Court banned its production and distribution. Over the years, other studies confirmed these findings, and the health hazards associated with endosulfan are now widely known and accepted (Patocka et al. 2016). The chemical, biochemical, environmental, and toxicological data of endosulfan reviewed by Patocka et al. (2016) showed its toxicological potential risk to human health that had been banned globally by the Persistent Organic Pollutants Review Committee in 2010.

## 14.7 Technological Intervention and Advancement in Development of Less Toxic Pesticides

Ecological engineering, biopesticides, nano-based smart pesticide formulations, stimuli-responsive nano-based pesticides are the emerging options to control pests with least effect to environment and human health. Ecological engineering for pest management is a new paradigm to enhance the natural enemies of pests in an agro-ecosystem and it relies on use of cultural techniques to bring about habitat manipulation and enhance biological control (Gurr et al. 2004). The key objective in ecological engineering is to make a conducive environment for the better survival of natural enemies of pests in the agro-ecosystem. In ecological engineering, habitat manipulation targets to provide natural enemies of pests with nectar, pollen, physical refuge, alternate prey, alternate hosts and living sites (Manage 2019). This can be achieved through plantation of appropriate companion plants like floral trap crops and repellent crops, through which the population of pollinators, predators and parasitoids that can be enhanced to manage the herbivorous insect pests (Manage 2019). As ecological engineering is knowledge intensive package of practice, lack of awareness and information sources to farmers about ecological engineering possess obstacles in adoption and scaling of this eco-friendly technology.

The microbiome or consortium of microorganisms not only act as a biological pesticide but also offers diverse plant growth-promoting attributes such as biological nitrogen fixation. Such microbiomes showed promising results as an alternative to chemical pesticides and are known to play a pivotal role against insects and pathogens. Still the efficacy and time to reduce pest attack is not convincing. *Moringa* leaf and stem extract may be used as a low cost and easily available

biopesticide (Kumar et al. 2019). Further strengthening research on bio-pesticides especially for emerging contaminants is the need of the hour to move forward sustainably in an eco-friendly manner.

In recent years, the application of nanotechnology to formulate nano-based pesticide has shown boundless potential for diminishing the indiscriminate use of pesticides and proposing environmentally safer alternatives. Smart nano-based pesticides are designed to efficiently deliver sufficient amounts of active ingredients in response to biotic and/or abiotic stressors that act as triggers, employing targeted and controlled release mechanisms (Camara et al. 2019). Presently, although stimuli-responsive systems are well developed in the area of medicine, their applications in agriculture principally in the pesticide field remain limited. Therefore, continued systematic and strategic research for the development of improved eco-friendly responsive, targeted, controlled-release pesticide formulations are required to excel a healthy and safer food production system (Camara et al. 2019).

Photocatalysis is one of the promising advanced oxidation technologies to alleviate pesticide induced contamination. Titanium dioxide ($TiO_2$) is the most popular photocatalyst due to its low cost, nontoxicity, high oxidizing abilities, and easy immobilization on various surfaces. Kanan et al. (2020) highlighted recent advancements in photocatalytic degradation of pesticides and major organic pollutants using $TiO_2$-based photocatalysts. Such research need to be more emphasised for the developing countries.

## 14.8 Conclusions and Future Thrust

Pesticides have proved to be a boon for the farmers by increasing agricultural yield manifold and providing innumerable benefits to society directly and indirectly in terms of food security. Nevertheless, the issue of hazards posed by pesticides to human health and the environment cannot be ignored. The outcomes of the case studies on ill-effects of pesticides in India is alarming and indicate a paradigm shift towards the knowledge-intensive farming system with a decreased footprint to the environment and human health. The studies reviewed in this paper have raised concerns about the safety of pesticides to use without affecting the non-target species and the environment. Moreover, the detrimental consequences of non-judicious over use of pesticides had been witnessed worldwide, and worsened the health and environment condition in developing countries particularly in India. Several case studies suggesting adverse effect of pesticide overuse on soil-plant-human-environment nexus in different regions of India was discussed throughout this review. Although the threats associated with pesticides cannot be eliminated, they could be circumvented in one way or the other to at least make it user and environment friendly. Integration of pesticides with its natural enemies has greater potential than is utilized at present and it could help in mitigating negative consequences of pesticide overuse. Low cost, efficient, target specific, eco-friendly integrated pest management package of practice needs to be developed based on site specific pest

problems to sustain the food production system sustainably. Indeed, strict policy framework, systematic and strategic responsible research, and ground-breaking awareness pathways are the demand of time in order to develop and implement for the betterment of society.

Recommendations for research in pesticides management to combat ill effects on soil, air, water and human health nexus:

- For now, pesticide free agriculture is nearer to impossible keeping in view of the food security and population growth, therefore, judicious use of pesticide is the need of the hour.
- Integrated pest management coupled with ecological engineering based interventions should be site specifically standardized, tested and disseminated to avail the benefits.
- Biopesticides, nano based eco-friendly encapsulation/formulation, and photocatalysis are the future research areas to strengthen pesticide free soil, air, water and human nexus.
- Development and use of a low-cost pesticide detection kit available to end-users to find out the permissible limit of residual pesticide in day to day consumable cereals, pulses, fruits and vegetables.

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