Chapter 7

Impact of agrochemicals on soil health

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7.1 Introduction

Agrochemicals are chemical products comprised of fertilizers, plant-protection chemicals or pesticides, and plant-growth hormones used in agriculture. Modern agriculture mostly depends on the use of various agrochemicals that have a significant contribution in enhancing efficient and economical crop production for meeting the food requirement of the fast-growing global population (Pal et al., 2006). For addressing the growing food demand, agrochemicals are profusely used in agriculture to bridge the gap between food production and consumption. However, unbalanced application of agrochemicals leads to environmental degradation and poses numerous challenges to agricultural ecosystems and soil health. For improving soil health and crop productivity, microorganisms play a significant role in the fundamental soil processes and actively participate in nutrient cycling (Jacoby et al., 2017). Soil degradation due to the overuse of agrochemicals has threatened the soil health sustenance and food security, which is a global problem (Jie et al., 2002). The fate of pesticides in the environment has created unwanted problems for nontarget organisms (e.g., beneficial microorganisms). The excess exposure of pesticides and their offsite mobility (transportation of infertile soils) instead of controlling target pests are of significant environmental concern in the current decade (Hafez and Thiemann, 2003). An ideal pesticide generally acts to kill/inactivate the target harmful organism, is biodegradable, and does not leach down to the groundwater. Unfortunately, this is a rare occurrence in modern agriculture scenarios (Johnsen et al., 2001). Due to the continuous use of agrochemicals in agriculture, appreciable quantities of degraded products and residues accumulate in the soil environment, which may pose severe risks of soil and food chain contamination (Aktar et al., 2009; Jayaraj et al., 2016). The long-term application of agrochemicals often resulted in heavy metal contamination of the environment and food chain as well, which consequently resulted in health-related problems and diseases in humans (Nasreddine and Parent-Massin, 2002). In some cases, microbial degradation of pesticides and their transformation in the soil may result in reduced toxicity of selected pesticide products (Kafilzadeh et al., 2015). At the same time the low performance of microbial activity due to extensive use of agrochemicals may adversely affect the soil health.

Microorganisms play an instrumental role in pursuing biodegradation of harmful chemicals and pollutants released because of anthropogenic activities. They also act as biocontrol agents for phytopathogens in agricultural soils (Canet et al., 2001). Soil microorganisms have thus been widely accepted as the bioindicators of soil health (Nielsen and Winding, 2002). Agrochemicals, particularly pesticides, having long persistence in the soil systems severely affect the soil microorganisms, thereby deteriorating the soil health (Prashar and Shah, 2016). Amendment of soils with agrochemicals has substantial impact on soil functions and nutrient cycling as well because these chemicals can influence several soil physicochemical properties such as soil moisture, pH, and soil organic carbon. Agrochemicals have a great influence on the shift of microbial population dynamics and communities of soil microorganisms along with many other biotic and abiotic factors ranging from soil characteristics to crop varieties. The use of agrochemicals primarily aims to ensure abundant food supply for humans, but it may have a negative impact on soil biological activity and diversity through direct or indirect actions. However, our knowledge about soil microbial ability to degrade agrochemicals and their influence on microbial diversity in the soil is still limited. Here, we shed some light on the environmental impact of agrochemicals focusing especially on their persistence level in soils and consequences on soil health and soil microorganisms.

7.2 Current use of agrochemicals in agriculture

Fig. 7.1 illustrates the broad classification of various agrochemicals used for growing crops. They include plant-protection chemicals/pesticides, plant-growth regulators, fertilizers, and others (e.g., soil conditioners and animal husbandry products). Presently, India is the leading producer of pesticides in Asia and ranks 12th in the world for the consumption of pesticides. In general, the pattern of pesticide usage in India and the world is different. An old estimate says 76% of the pesticides used in India are insecticides, as against 44% globally (Mathur, 1999). Among pesticide the consumption of herbicides and fungicides is comparatively less heavy. In India the major share of

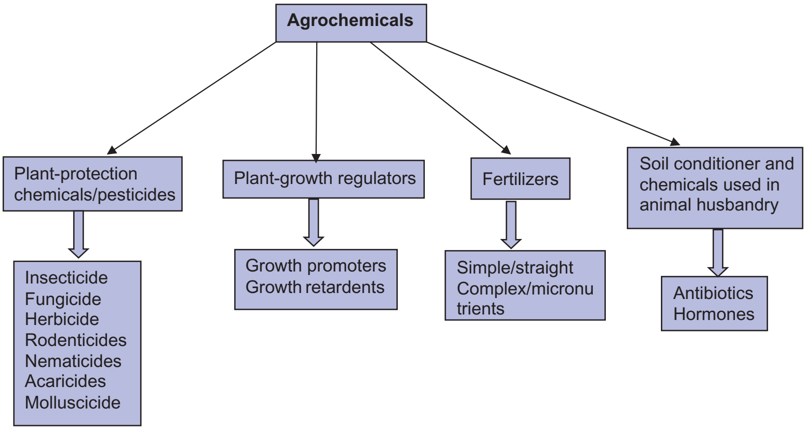

FIGURE 7.1 Broad classification of agrochemicals.

consumption of pesticides in India is 45% for the cotton crops (5% is the cropped area), followed by 20% for the rice (24% is the cropped area), and 13%−24% for chilies/vegetables/fruits (3% is the cropped area). Though India's average consumption of pesticides is far lesser than many other developed economies, the problem of pesticide residues is very intense in India (Abhilash and Singh, 2009). After the green revolution, agrochemicals played a significant role in almost doubling the country's food production in comparison to before. Table 7.1 lists the major kinds of pesticides used in agriculture. Several reports have outlined that aquatic and terrestrial ecosystems are at emergent risks due to the exhaustive application of fertilizers and pesticides besides their confirmed association with some of the human health disorders such as rheumatoid arthritis, kidney diseases, and different cancers (Jayasumana et al., 2015; Parks et al., 2016). It is, therefore, necessary to consider risks and challenges posed by agrochemical application in agriculture for safeguarding the human health, ecosystem, and environment.

The present world population stands at 7.2 billion which is projected to reach 9.3 billion by 2050 (FICCI, 2016). The exponential growth of population will certainly lead to a higher demand for food and feed. To attain the food and nutritional security for the increasing population, an alternative sustainable approach is urgently required that enhances productivity against the existing scenario of poor yields and shrinking farm holdings. Moreover, attacks by insect pests, weeds, and diseases damage approximately 25% of the global food production, which does not promise well for farming given the potential challenges ahead (Koli et al., 2019). In 2014 the use of other pesticides (mainly organophosphate) accounted for the major proportion of total pesticides (53.84%), followed by herbicides (25.10%), and then by fungicides and bactericides (12.06%), insecticides (7.50%), and plant-growth regulators (1.24%) (Fig. 7.2). The use of insecticides includes mostly

TABLE 7.1 Kinds of pesticides used in agricultural production.

Types of pesticides		Name of pesticides
Insecticides	Organic nitrogen	Benzoylphenylurea, chlordimeform
	Organic phosphorus	Acephate, azinphos-methyl, bromophos, chlorpyrifos, coumaphos, diazinon, dimethoate, dioxathion, disulfoton, diazinon, ectophos, fenitrothion, fenitrooxon, fonofos, glyphosate, leptophos, malathion, mathamidophos, parathion, phenthoate, profenofos, phorate, phosmet, phosphothion, trichlorfon
	Organic chlorine	Aldrin, chlordane, DDT, dieldrin, dicofol, endosulfan, endrin, fipronil, heptachlor, lindane, γ-benzene hexachloride, γ-hexachlorocyclohexane
	Carbamate	Aldicarb, carbaryl, carbofuran, carbosulfan, cartap
	Pyrethroid	Cypermethrin, chlorfenvinphos, deltamethrin, fenvalerate, flumethrin, permethrin, ivermectin
	Insect growth regulators	Azadirachtin, benzoylphenylurea, diflubenzuron, methoxyfenozide, pyriproxyfen, spinosad, tebufenozide
Acaricides	Amitraz, coumaphos, dimethoate, fenpyroximate, formic acid, menthol, tau-fluvalinate, thymol	
Herbicides	Acetanilides, alachlor, barban, chlorbromuron, chlorophenoxy, dalapon, diuron, glyphosate, linuron, monuron, neburon, pendimethalin, pentachlorophenol, propham, salted iron phosphorus, swep, 2,4-D, 2,4,5-T	
Bactericides	Bayleton, blue copper, chlorothalonil, copper hydrochloride, copper oxychloride, copper sulfate, different rice blast net, dithane, dithiocarbamates, mancozeb, metalaxyl, methyl phosphorus, impact, polytrin, Ridomil, rice blast net, triazoles, thiocarbamates, thiovit	

$DDT, p, p -$ Dichlorodiphenyltrichloroethane.
Source: Adapted from Huang, Y., Xiao, L., Li, F., Xiao, M., Lin, D., Long, X., et al., 2018. Microbial degradation of pesticide residues and an emphasis on the degradation of cypermethrin and 3-phenoxy benzoic acid: a review. Molecules 23(9), 2313.

organophosphates, followed by pyrethroids, carbamates, botanical and biological products, chlorinated hydrocarbons, and pyrethroids. The most commonly used herbicides include amides, followed by phenoxy hormone products, bipiridils, triazines, urea derivatives, dinitroanilines, carbamates, sulfonylurea, and uracil. Among the fungicides and bactericides, inorganic ones are the most commonly used, followed by other fungicides, dithiocarbamates, triazoles and diazoles, benzimidazoles, diazines, morpholines,

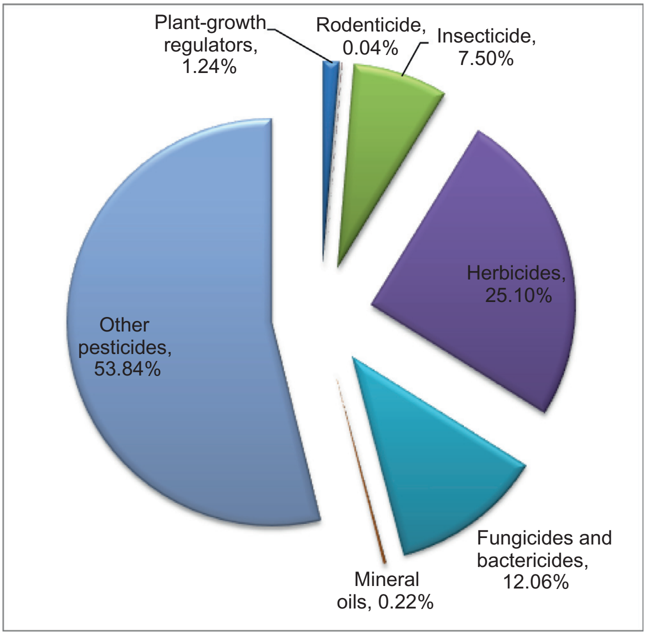

FIGURE 7.2 Proportions of global pesticide use in 2014. *Adapted from Zhang, W., 2018. Global pesticide use: profile, trend, cost/benefit and more. Proc. Int. Acad. Ecol. Environ. Sci. 8 (1), 1 (Zhang, 2018).*

seed-treating fungicides, disinfectants, etc. Among rodenticides, anticoagulants are the mostly used ones, followed by narcotics.

In addition to agrochemicals, fertilizer consumption is highest in the Asia region in the world. In total, East Asia and South Asia, fertilizer nutrient consumption is about 58.5% of the world total. The share of Asia in the world consumption of nitrogen, phosphate, and potash is 62.1%, 57.6%, and 46.4%, respectively (FAO, 2015). India ranks third in the world for fertilizer production after China and the United States, and second for fertilizer consumption after China. FAO estimated that between 2015 and 2030, fertilizer consumption in the world is expected to increase from 138 million tons in 1997/98 to 182 million tons in 2030, at an annual growth rate of 1.0% (Bruinsma, 2017). Cereals crops such as wheat, rice, and maize are considered as dominant fertilizer consuming crops. The average annual consumption increased from 21.6 million metric tonnes in 2006–07 to 26.6 MT in 2017–18 (FAI, 2018).

It is also evident that increased consumption of agrochemicals has adversely affected soil fertility and deteriorated sustainable crop production (Sharma, 2003). Because of awareness of the negative impacts of the use of extensive pesticide on the ecology and environment, and due to the inception of integrated pest-management practices and transgenic crops, the consumption of chemical pesticides has significantly decreased (Peshin and Zhang, 2014).

Pesticides are extensively applied in general against a wide range of pests infesting agricultural produces. It was reported that approximately one-third of the agricultural products is produced by using pesticides (Liu et al., 2002; Zhang et al., 2011). FAO (2013) computed that the average application rates of pesticides in arable farming were found highest in (6.5−60 kg/ha) the Asia region and in some countries of South America. The amount of applied pesticides that reach the target organism is only 0.1%, while the remaining bulk amount contaminates the soil and water environments (Carriger et al., 2006; Pimentel, 1995). With the growing use of pesticides in modern agriculture, there is a severe concern about the impact of these chemicals on the composition of soil microorganisms (Andrea et al., 2000; Baxter and Cummings, 2008). The applied pesticides may pose a toxic effect on the indigenous microorganisms, disturb the soil ecosystem, and thus may affect human health by entering into the food chain. Over the last two decades, numerous studies reported the exposure of pesticides into the human bloodstream and adipose tissues causing neuronal disorder, degenerative diseases, abnormal fetal growth, congenital anomalies, and cancer (Asghar et al., 2016; Ridolfi et al., 2014; Singh et al., 2018). After the green revolution the indiscriminate use and improper handling of pesticides in agriculture have caused severe human health-related problems in many developing countries (Dasgupta et al., 2007).

Many researchers (Littlefield-Wyer et al., 2008; Singh and Kumar, 2008; Dutta et al., 2010) have reported adverse impacts of pesticides on soil microbial diversity and activities. Similarly, pesticides also affect soil biochemical processes driven by microbial metabolic and enzymatic reactions. They may adversely affect the biotransformation of organic compounds by beneficial soil microflora and enzymatic actions modifying the nutrient dynamics and bioavailability (Hussain et al., 2009). The assay of soil enzymatic activity serves as bioindicators of soil ecosystem status, and the applied pesticides can influence this (Utobo and Tewari, 2015). Soil microorganisms also play a critical role in the degradation of pesticides in the soil environment (Hussain et al., 2007a,b; Huang et al., 2018). Microbial assimilation of degradation products may result in increased population sizes of microorganisms and decreased persistence of pesticide residues (Tyess et al., 2006; Doolotkeldieva et al., 2018; Velázquez-Fernández et al., 2012).

Nowadays, molecular techniques are available to elucidate the impact of agrochemical pollution on soil microbial community structure and functioning (Mattsson, 2016; Tipayno et al., 2018). The soil biological activities and beneficial microorganisms have major contribution in maintaining the health status of the soil, which is often ignored while using various agrochemicals in agriculture (Lehman et al., 2015). While the soil organic matter levels have observed a declining trend, the use of chemical inputs in soils has intensified (Patra et al., 2016). Pesticides, which are persistent in the soil, slowly break down and result in a source of contamination in soil and groundwater (Pérez-Lucas et al., 2018).

7.3 Fate and toxicity of agrochemicals in soil

Following their entry into the soil environment, pesticides undergo a variety of degradation/transformation processes (Pal et al., 2006). The combination of mechanisms involved in the degradation of pesticides in the soil includes microbial degradation, chemical hydrolysis, photolysis, volatilization, leaching, and surface runoff (Fig. 7.3). In general, the degradation of pesticides depends on several physicochemical factors of soils and soil processes, including adsorption/desorption, plant uptake, surface transport, subsurface transport, volatilization, microbial metabolism, and chemical conversion. Pesticides in the environment likely to degraded or not degraded, immobilized, detoxified, or removed with the harvested crops are subject to their movement away from the point of application (Gao et al., 2012). Pesticides are undergoes a various kind of loses to the environment is, and major loss pathways are volatilization into the atmosphere, aerial drift, runoff to surface water bodies in dissolved and particulate forms, and leaching into groundwater basins (Fig. 7.3). The fate and transfer pathways of pesticides are complex, requiring further studies of their chemical properties (especially for newly introduced chemical products), transformations (breakdown) by biotic and abiotic means, and the physical transport process. The previous

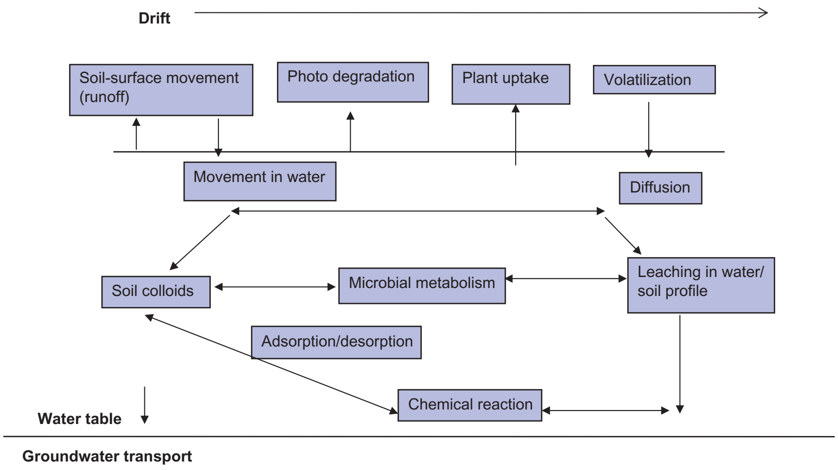

FIGURE 7.3 Fates of pesticide in the soil systems.

transformation and transport processes are strongly impacted by the site-specific conditions and management practices.

The transformation of pesticides can be categorized as processes such as complete removal of chemicals from the environment, localized losses, and transported away. The balance of these fate processes is regulated by both the characteristics and nature of the chemicals and the conditions and properties of the soils involved. General properties of the pesticide include its chemical composition and structure, volatility, solubility in aqueous systems, mode of formulation, and application (Tano, 2011). It is therefore essential to understand all of these interactions and their environmental significance. The research found a longer persistence of pesticides in soils as compared to that in plants or animals because the chemical residues are more readily metabolized in an actively growing living system than in a relatively static soil system (Edwards, 1975).

The persistence of pesticides in the soil is measured by their half-life, the rate at which the compound breaks down in the soil (US EPA, 2012). The longer the half-life, the longer the compound will stay in water or soil in its original form, therefore more prone to leaching through the soil. Depending on their half-lives, pesticides have been assigned various levels of persistence in soil. Among the pesticide groups (Table 7.1), organochlorines are considered as the most persistent pesticides in the environment as they contain more than five chlorine atoms in each molecule that poses the degradation process very slow. The US EPA has classified several organochlorine pesticides, including aldrin; dieldrin; chlordane; *p*,*p*-dichlorodiphenyltrichloroethane (DDT); mirex; and toxaphene as highly persistent bioaccumulative and toxic (PBT) chemicals. The PBT pollutants thus pose a risk to the human health and ecosystem. These pesticides generally bind strongly to soil particles and may remain in surface soils from a few months to many years (US EPA, 2000). While persistent pesticides tend to have long-term effectiveness in pest control, they have toxic and harmful effects on the soil flora and fauna. At the same time, they pose chronic toxicity to the environment (Prashar and Shah, 2016, Mahmood et al., 2016). Thus pesticides that persist in the soil longer than the requisite time for target-pest control are unwanted. Further, the breakdown of pesticide molecules should not result in the release of any toxic substances in the soil. Residual levels of pesticides in soils generally depend on properties of the soil, quantity of applications, and growth stages of the plants (Cycon and Piotrowska-Seget, 2007).

Agrochemicals once released into the air or water will also end up in soils. Among the organic pollutants, some are known as persistent organic pollutants (POPs). The POPs break down very slowly in the environment and persist for an extended period, thereby resulting in various hazardous impacts in the soil. Continuous and excessive use of POP agrochemicals, particularly pesticide compounds, thus led to serious challenges to the soil ecosystem, posing a clear threat to our food security (Aktar et al., 2009).

Ecological toxicity may occur due to soil pollution with agrochemicals under agricultural production scenarios. It may also result in the accumulation of hazardous heavy metals and other persistent organic residues in the soil leading to serious consequences in the environment. Some agrochemicals such as fertilizers and pesticides are rich heavy metal concentrations including Cd and Cu that pose toxicity to the soil environment (Kabata-Pendias and Pendias, 1992; Chen and Pu, 2007).

7.4 Effects on soil biota and soil microflora

Soil biota and soil microflora are the key elements that respond quickly to any amendment or agrochemical entering into the soil system. The effects of agrochemicals have their fast response to soil microflora, reflecting either negative or positive influences of pesticide treatments. These responses are commonly used in ecotoxicological assessments to evaluate the impact of agrochemicals on the soil system and indicator of soil disturbance (Doelman and Vonk, 1994; Edwards et al., 1996; Chowdhury et al., 2008).

7.4.1 Effect on soil enzymatic activity

Agrochemicals, particularly pesticides, that reach the soil may adversely affect the microbial metabolism or can alter the soil enzymatic activity (Floch et al., 2011). Soils, in general, comprise various enzymatic pools that consist of free enzymes, immobilized extracellular enzymes, and enzymes excreted by (or within) microorganisms (Mayanglambam et al., 2005; Hussain et al., 2009). These enzymes are the key indicators of biological equilibrium, including soil fertility and quality. Biodegradation of both agro-pesticides and natural chemical substances in the soil is catalyzed by these enzymatic pools (Floch et al., 2011; Kizilkaya et al., 2012). Due to this, measuring the change in enzymatic activity has been classified as a biological indicator to identify the impact of chemical substances including pesticides on soil biological processes and functions (Sannino and Gianfreda, 2001; Romero et al., 2010). It is assumed that measuring the change in enzyme activity is an early indicator of soil degradation as compared to the chemical or physical parameters (Dick, 1994). Several research studies were undertaken to show both increase and decrease of soil enzyme activities such as hydrolases, oxidoreductases, and dehydrogenase due to the presence of pesticides (Table 7.2) (Riah et al., 2014; Megharaj et al., 1999). Table 7.2 shows that the effects of pesticides widely vary on soil enzymatic activities based upon the pesticide types, soil types, and prevailing conditions. Therefore it is prudent to test newly arriving commercial pesticide products rigorously before their widespread usage by the farming communities.

TABLE 7.2 Effect of pesticides on the activities of soil enzymes.

The enzyme (function in soil)	Examples of the pesticides applied	Comments
Nitrogenase (an enzyme used by organisms to fix atmospheric nitrogen gas)	Carbendazim, imazetapir, thiram, captan, carbofuran, 2,4-D, quinalphos, monocrotophos, endosulfan, γ-HCH, butachlors Terbutryn, simazine, prometryn Brominal, fenvalerate, Cuprosan Oxafun, Funaben, Baytan, pretilachlor, benthiocarb, cinmethylin, anilofos Methabenzthiazuron, terbutryn, linuron	Pesticide decrease or inhibited the nitrogenase activity in laboratory or field conditions (Chalam et al., 1996, 1997; Gallori et al., 1991; Martinez-Toledo et al., 1998; Niewiadomska, 2004; Niewiadomska and Klama, 2005; Prasad et al., 2011, Singh and Wright, 1999; Hammouda, 1999, Omar and Abd-Alla, 1992; Di Ciocco and Cáceres, 1997; Khan et al., 2006) Field doses of the fungicides did not affect nitrogenase activity of methylotrophic bacteria, but higher doses suppressed the activity (Durska, 2004) Pesticides stimulated the nitrogenase activity (Patnaik et al., 1995; Kanungo et al., 1995)
Phosphatase (mineralizes organic P compounds to inorganic P)	2,4-D, nitrapyrin, mefenoxam, metalaxyl Monocrotophos, chlorpyrifos, mancozeb, and carbendazim Quinalphos Diazinon, imidacloprid, lindane Glufosinate ammonium	Inhibited (Tu, 1981; Monkiedje et al., 2002) Activity increased, but higher concentration or increasing incubation period had inhibitory effects (Madhuri and Rangaswamy, 2002; Srinivasulu et al., 2012) Initially inhibited but later on activity was restored (Mayanglambam et al., 2005) Diazinon did not affect, imidacloprid increased while lindane decreased the enzyme when applied as seed treatment in groundnut field (Singh and Singh, 2005) Initial inhibition of phosphatase in sandy loam and clay loam soils (Ismail et al., 1995)

(*Continued*)

TABLE 7.2 (Continued)

The enzyme (function in soil)	Examples of the pesticides applied	Comments
Urease (catalyzes the hydrolysis of urea into CO_2 and NH_3 and is a key component in the nitrogen cycle in soils)	Isoproturon, benomyl, captan, diazinon, profenofos	Increase in urease activity (Chen et al., 2001; Nowak et al., 2004) Pesticide reduced/inhibited urease activity (Abdel-Mallek et al., 1994; Ingram et al., 2005)
DHA: an oxidoreductase enzyme that catalyzes the removal of hydrogen	Azadirachtin, acetamiprid, quinalphos, glyphosate Atrazine and northrin	Positive/stimulatory influence on DHA (Singh and Kumar, 2008; Kizilkaya et al., 2012) Initially inhibited, but later activity was restored (Andrea et al., 2000; Mayanglambam et al., 2005) Herbicides stimulated DHA of the microbial community at lower and inhibited it at higher concentrations (Nweke et al., 2007)
Invertase (hydrolyzes sucrose to fructose and glucose)	Atrazine, carbaryl, paraquat	Inhibited invertase activity (Gianfreda et al., 1995; Sannino and Gianfreda, 2001)
β-Glucosidase (hydrolyzes disaccharides in soil to form β-glucose)	Metalaxyl, Ridomil Gold Plus Copper	Enzyme activity increased and then decreased (Sukul, 2006), inhibited (Demanou et al., 2004)
Cellulase (hydrolyzes cellulose to D-glucose)	Benlate, captan, brominal	Inhibited enzyme activity (Arinze and Yubedee, 2000; Omar and Abdel-Sater, 2001)
Arylsulphatase (an enzyme that hydrolyzes aryl sulfates)	Cinosulfuron, prosulfuron, thifensulfuron methyl, triasulfuron	Decreased enzyme activity (Sofo et al., 2012)

DHA, Dehydrogenase; *HCH*, hexachlorocyclohexane.

7.4.2 Effect on nutrient cycling microbial communities

Although pesticides are intended to protect crops, they may affect the soil environment altering the equilibrium of soil processes over short or long periods. The resultant changes in the soil microbial activity due to repeated application depending on the intensity and spectrum of the activity and persistence of the original pesticide or their metabolites product (Margni et al., 2002). Culturable diversity, biochemical activities, and microbial community structure may also be affected by pesticide (Martinez-Toledo et al., 1998; Smith et al., 2000; Chen et al., 2001; Cycoń and Kaczyńska, 2004; Cycon and Piotrowska-Seget, 2007). Pesticides that interrupt the activities of soil microorganisms involved in the nutritional cycling of soils result in adverse consequences on the soil ecosystem.

Agrochemicals especially pesticide has direct impact on various soil microorganisms and their metabolic function (Singh and Walker, 2006) and may alter the physiological and biochemical properties of soil microorganisms. Assessment of microbial biomass in the soil is generally considered a key indicator of soil microbial activities and provides a direct measurement of the linkage between soil microbial activities and the essential nutrient cycling and other ecosystem services (Schultz and Urban, 2008). Pampulha and Oliveira (2006) speculated the negative impacts of pesticides on soil microbial biomass and soil respiration. Generally, a decline in soil respiration in pesticide-treated soil reflects the significant reduction in microbial biomass (Chen et al., 2001), or increase in respiration implies the enhanced proliferation of soil bacteria (Haney et al., 2000; Wardle et al., 1994). Diverse groups of soil microbes are capable of using applied pesticide molecules as a source of energy and nutrients to multiply, whereas other pesticides may pose toxicity to microorganisms (Johnsen et al., 2001). Likewise, application of pesticides may reduce the microbial diversity but may increase their functional diversity (Wang et al., 2006). Sometimes, pesticides may demonstrate a tendency of reversible stimulatory/inhibitory effects on soil microorganisms (Pampulha and Oliveira, 2006). Pesticide application may also inhibit or kill certain group(s) of microorganisms, and other groups of microorganisms may flourish out of competition among the groups. For instance, Chen et al. (2001) reported that fungicide applications killed or reduced the activity of certain fungi, which led to a rapid flush of bacterial activity.

Similarly, Lopez et al. (2006) reported that heterotrophic bacteria as well as culturable phosphate-solubilizing microorganisms enhanced in lake water samples when treated with the herbicide simazine. Sometimes, initially the microbial population is affected by a pesticide application, but later due to acclimation, the population comes back to its normal level or even increases (Niewiadomska, 2004). This indicates alterations in microbial catabolic metabolism that may be either due to induced pesticide degradation potentialities or due to a shift within the microbial community (Ortiz-Hernández et al., 2013; Yale et al., 2017). A detailed description of the impacts of various pesticides on soil microbial communities is summarized in Table 7.3.

Soil microorganisms are essential for the maintenance of soil structure, and decomposition and transformation of organic matter are making nutrients available to plants. External agricultural inputs, namely, mineral fertilizers, organic amendments, microbial culture, and plant-protection chemicals/pesticides are applied with the ultimate goal of maximizing the crop productivity and economic returns, while side effects on soil beneficial organisms are mostly neglected. The excessive agrochemical application in agriculture reduces the biodiversity of the soil (McLaughlin and Mineau, 1995). The communities of beneficial soil microorganisms have been inhibited due to excessive use of pesticides, which limits the available form of nutrients such as nitrogen, phosphorus, and potassium in soils (Sardar and Kole, 2005), thereby degrading the soil quality. Important soil processes such as mineralization, nitrification, and phosphorus recycling are directly dependent on the balanced existence of various groups of organisms in the soil. However, extensive pesticide usage disturbs the various actions of soil enzymes that are pivotal for the processes mentioned above and organic matter turnover. Fungicides generally had more significant effects on soil organisms than insecticides or herbicides. As these chemicals are applied to minimized fungal borne diseases, they will also influence beneficial soil fungi and other soil organisms involved in the nutrient cycling process. Studies found that copper-based fungicides have significant negative effects that cause reduction of earthworm population in soils for a longer period of time (Van Zwieten et al., 2004; Eijsackers et al., 2005). Merrington et al. (2002) further demonstrated significant reductions in microbial biomass, while respiration rates were increased, and showed conclusively that copper residues resulted in stressed microbes. Particularly, organophosphate groups of insecticide such as chlorpyrifos, quinalphos, dimethoate, diazinon, and malathion have a wide range of impacts including changes in the bacterial and fungal numbers in soils (Pandey and Singh, 2004), varied effects on soil enzyme activities (Singh and Singh, 2005), as well as depletion in collembolan density (Endlweber et al., 2006) and earthworm reproduction (Panda and Sahu, 1999). A few studies reported that some organochlorine and organophosphorus pesticides suppress symbiotic nitrogen fixation resulting in lower crop production (Fox et al., 2007; Potera, 2007).

7.5 A consequence of agrochemicals on soil health

Soil is a nonrenewable resource, and its preservation is essential for food security and a sustainable future. Soil is primarily responsible for providing most of the food items consumed by mankind and also vital in maintaining

TABLE 7.3 Effect of pesticides on soil microbial communities.

Pesticide	Microbial species	Comments	References
Atrazine, isoproturon, metribuzin, and sulfosulfuron	*Bradyrhizobium* sp.	Adversely affected *Bradyrhizobium* sp.	Khan et al. (2006)
Phorate, carbofuran, carbosulfan, thiamethoxam, imidacloprid, chlorpyrifos, monocrotophos	Soil microflora	No significant change in the total viable count of bacteria	Sarnaik et al. (2006)
Methamidophos	Soil microflora	Reduction of microbial biomass (41%–83%)	Wang et al. (2006)
Metsulfuron-methyl	Soil microorganisms	Inhibited heterotrophic S-oxidizing and S-reducing bacteria but increased fungi	He et al. (2006)
Metalaxyl	Microbial biomass	Decreased microbial biomass	Sukul and Spiteller (2001)
Mefenoxam, metalaxyl	Soil microorganisms	Inhibited N_2-fixing bacteria	Monkiedje et al. (2002)
Carbendazim, imazetapir, thiram	Soil microorganisms	Combination of fungicide and herbicide reduced while herbicide alone increased soil microorganisms	Niewiadomska (2004)
Carbofuran, ethion, hexaconazole	Soil microorganisms	Adversely affected soil microorganisms	Kalam and Mukherjee (2001)
Bensulfuron methyl, metsulfuron methyl	Microbial biomass	Decreased microbial biomass-C, and N	El-Ghamry et al. (2001)
HCH, phorate, carbofuran, fenvalerate	Soil microorganisms	N_2-fixing bacteria, and P-solubilizing microorganisms Increased soil microbial population	Das and Mukherjee (1998, 2000)

Phorate, malathion	Soil microorganisms	Phorate decreased a total number of bacteria and N_2-fixing bacteria, but malathion Increased denitrifying bacteria. Nitrifying and fungal populations were not affected	Gonzalez-Lopez et al. (1993)
Captan, apron, arrest, crown	*Rhizobium ciceri*	Except for crown, all fungicides decreased viable counts of rhizobia	Kyei-Boahen et al. (2001)
2,4-D	*Rhizobium* sp.	Inhibited the growth of *Rhizobium* sp.	Fabra et al. (1997)
Atrazine	*Chlamydomonas reinhardtii Pseudokirchneriella subcapitata*	Inhibited the growth of algae	Reboud et al. (2007) and Cedergreen et al. (2007)
Agroxone, Atranex, and 2,4-damine	*Rhizobium phaseoli*, *Azotobacter vinelandii*	2,4-Damine was the most toxic of the herbicides and *A. vinelandii* was the most sensitive to the herbicides	Adeleye et al. (2004)
Brominal, fenvalerate, Cuprosan	*Azotobacter chroococcum*, *Azospirillum brasilense*, *Azospirillum lipoferum*	Reduced respiration rate and protein contents of diazotrophs	Omar and Abd-Alla (1992)
γ-HCH, 2,4-D, anilofos, carbofuran	N_2-fixing *Azotobacter* and *AzospirillumAzotobacter* and *Azospirillum* populations	γ-HCH stimulated populations and inhibited anaerobic N_2-fixing bacteria, while carbofuran 2,4-D and anilofos stimulated anaerobic N_2-fixing bacteria	Patnaik et al. (1995, 1996) and Kanungo et al. (1995)
Monocrotophos, lindane, dichlorvos, endosulfan, chlorpyrifos, malathion	*Gluconacetobacter diazotrophicus*	Affected cell morphology and resulted in large number of pleomorphic cells	Madhaiyan et al. (2006)
Captan	Aerobic N_2-fixing, denitrifying, nitrifying bacteria, fungi	Fungi, nitrifying, and N_2-fixing bacteria significantly decreased while denitrifying bacteria increased	Martinez-Toledo et al. (1998)

(*Continued*)

TABLE 7.3 (Continued)

Pesticide	Microbial species	Comments	References
Methylpyrimifos, chlorpyrifos, profenofos	Aerobic N_2-fixing, denitrifying, nitrifying bacteria, fungi	Decreased microbial populations	Martinez-Toledo et al. (1992a,b)
Diazinon, imidacloprid	Urease-producing bacterium	Inhibited the growth of *Proteus vulgaris*, a urease-producing bacterium	Ingram et al. (2005)
Isoproturon	Nitroso-, nitro-, urea-hydrolyzing bacteria; actinomycetes; fungi	Increased bacterial count and decreased actinomycetes and fungi	Nowak et al. (2004)
Butachlor	Anaerobic bacteria	Stimulated anaerobic fermentative and sulfate-reducing bacteria while inhibited acetogenic bacteria in paddy soil	Min et al. (2001)
Glufosinate ammonium	Bacteria and fungi	The herbicide initially decreased bacterial and fungal populations significantly in clay loam and loam soils	Ismail et al. (1995)
Isoproturon	Actinomycetes and fungi	Biodegradation of isoproturon favored bacterial growth while suppressing actinomycetes and fungi	Nowak et al. (2004)
Methamidophos	Soil microbes	The population of some microbes increased in soil but the total biomass decreased	Wang et al. (2006)

HCH, Hexachlorocyclohexane.

environmental quality at various levels. Hence, maintenance of soil health is very necessary in order to meet the ever-increasing demand for food and sustainable development of agriculture. The term soil health has been defined as "the capacity of the soil to function within an ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, to promote plant and animal health and to support human health and habitation" (Doran and Parkin, 1994). Another widely accepted definition of this term is "continued capacity of soil to function as a vital living system, within the ecosystem and land use boundaries, to sustain biological productivity, promote the quality of air and water, and maintain the plant, animal and human health" (Avidano et al., 2005). In a wider perspective, it is the ability of soil to perform and function according to its potential (Doran and Safley, 1997).

The terminologies soil health and soil quality are often used interchangeably in order to describe the capacity of soil to support plant growth while it does not undergo degradation (Harris and Bezdicek, 1994). Ever since the beginning of practices of farming with agrochemicals, mankind has been highly instrumental in depleting the soil health in numerous ways. Extensive chemical inputs in the form of inorganic fertilizers and pesticides have proved as one of the major causes of poor soil health. Since soil biological properties are strongly impacted by the prevailing physicochemical environment, it may be drawn that microbial activity and their functional diversity are important indicators of soil health. Hence, the assessment of soil microflora may be considered as a potential tool to provide vital insight into the soil health and its function.

Soil health also encompasses the impacts that soil use and management can have on water and air quality and on human and animal health. Inappropriate use of agrochemicals, amongst common farming practices, can significantly contribute to the soil-degradation process. There is evidence that prolonged use of heavy doses of fertilizers can result in soils to become more acidic that has serious implications in terms of long-term economic productivity of soils. Imbalanced or excessive use of agrochemicals is the most important cause of groundwater pollution or surface water bodies resulting from unsustainable use of applied nutrients. Many agrochemicals are persistent soil contaminants, whose impact may endure for decades and negatively impact the sustainable soil conservation endeavor. Pesticides enter the soil system through foliage spray, wash-off from treated foliage, and release from residue substances from the treated seeds in the soil. The bioavailability of pesticides in the soil also has a significant impact on beneficial plants and soil organisms as well as on human and animal health. Pesticides can move off-site, contaminating the surface water, or leaching through the soil profile contaminating the groundwater, possibly causing adverse impacts on the entire aquatic ecosystem.

The most important impact of soil degradation due to soil pollution is a substantial reduction in the productivity of the soil. Soil-degradation processes are generally threatening and show an adverse effect on various soil properties that may reduce the capacity of soils to absorb rainwater, implying the increased possibility of runoff and erosion (Gregory et al., 2015). Soil degradation processes also result in the decline of aboveground and underground microbial diversity, reducing the soil and water quality and overall ecosystem health. Mechanized farming with agrochemicals caused nutrient depletion and wide-scale soil erosion and groundwater pollution.

Major risks associated with frequent use of pesticides and fertilizers are soil and water pollution, the emergence of resistant strains of weeds and pests to pesticides, ecological instability, and toxicity to human and other organisms (Lamichhane et al., 2016; Aktar et al., 2009). Excessive use of fertilizers has led to the contamination of groundwater with nitrate and phosphate—chemical compounds that are poisonous to humans and animals when present in large concentrations. Also, the runoff of fertilizers into streams, lakes, and other surface waters can increase the growth of algae, leading to the death of aquatic animals.

As per the guidelines for the approval of pesticides, information regarding the effects of pesticides on soil microorganisms and soil fertility is required. However, the relationships of different structures of pesticides with the growth of various groups of soil microorganisms are difficult to predict. Some pesticides stimulate the growth of microorganisms, but other pesticides have depressive effects or negligible effects on microorganisms (Tables 7.2 and 7.3). For example, carbofuran application stimulated the numbers of *Azospirillum* and other anaerobic nitrogen fixers in both flooded and nonflooded soils, whereas butachlor reduced the growth of *Azospirillum* and aerobic nitrogen fixers in nonflooded soil (Lo, 2010). Herbicides such as diuron and chlorotoluron exhibited no difference between treated and nontreated soils, and linuron showed a marked difference (El Fantroussi et al., 1999). Phosphorus-containing herbicide glyphosate and insecticide methamidophos triggered soil microbial population, but another phosphorus-containing insecticide fenamiphos was detrimental to nitrifying bacteria (Lo, 2010, Cáceres et al., 2009).

In agriculture, pesticides are extensively applied as a part of pest control strategies. Due to xenobiotic nature, pesticides may negatively affect the populations of beneficial soil microorganisms and their associated biotransformation of nutrients in the soil (Suman, et al., 2018). Pesticide-contaminated soils also inactivate a number of beneficial microorganisms such as nitrogen-fixing rhizobacteria affecting molecular interaction in the vital process of biological nitrogen fixation and phosphorus solubilizing microorganisms (Hussain et al., 2009). Similarly, several reports are available to show that the use of pesticides may reduce the activities of various soil enzymes that are the key indicators of soil health (Table 7.2). The applied pesticides may also affect soil nutrient cycling and associated biochemical processes such as organic matter mineralization, nitrification, denitrification, ammonification, redox reactions, and methanogenesis. However, a few reports reveal some positive effects of applied agrochemicals on soil health (Aktar et al., 2009).

7.6 Conclusion

Several researchers tried to find the effect of agrochemicals on soil microbiological and biochemical health, but the effect is dependent on many biotic and abiotic factors and soil properties. Use of agrochemicals in agriculture for a long time may create a toxic impact on soil microbial activities and soil processes affecting soil nutrient cycling and crop production. The soil health is interlinked with the soil biochemical health and soil enzyme activities, and they can be the most important quality indicators in agrochemical-contaminated soils. It is also evident from the literature that an ideal and optimal use of agrochemicals is needed to maintain the ecological balance and health sustenance of the soil. Pesticide application has many pronounced effects on the overall health of the soil than the other groups of agrochemicals. Among all the groups of soil microbes, certain microbes such as fungi and actinomycetes are more efficient to metabolize pesticide xenobiotics than bacteria. Benefits of agrochemicals are also obtained by using their judicial application that controls harmful pests and phytopathogens. Environmental pollution, particularly heavy metal contamination and nutrient toxicity, was also noticed due to improper use of agrochemicals. Recent approaches for a precise and better application of agrochemicals would be useful in reducing ecotoxic effects and preventing human health hazards. Moreover, further developments to popularize alternative protocols, such as biopesticides, organic pesticides, novel biocontrol agents, and nanopesticides, should be emphasized to avoid the careless application of agrochemicals.

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