Chapter 24
Impact of Pesticides on Microbial Population

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Abstract Microbes are constituting elements of the soil environment and their abundance, enzymatic activity, degradation process, and biodiversity indicate the balance in the agro-ecological system. It is necessary to keep strengthening the scientific basis of modern agriculture because pesticides may be purposefully used only if their persistence, bioaccumulation, and toxicity in agro-ecosystems are strictly controlled. The use of agrochemicals, such as chemical fertilisers and pesticides, is important in modern crop management strategies (mainly insecticides and herbicides). Pesticide poisoning affects three million people worldwide, according to the WHO. Long-term and indiscriminate pesticide use has serious negative consequences for soil microbes, the nutrient cycle, the decomposition process, and the atmosphere, resulting in long-term negative consequences for food stability, human health, and the environment. Pesticide application can alter microbial diversity, which can be detrimental to plant growth and development by decreasing nutrient availability or disrupting the nutrient cycle. Therefore, the qualitative, innovative, and demand-driven pest management is the need of the hour. Hence, this chapter covers the positive and negative consequences of pesticides on microbes and their environment and current issues about the extensive use of pesticides.

Keywords Microbes · Pesticides · Decomposition processes · Nutrient cycle

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24.1 Introduction

Pesticides are effective agrochemicals that are used to protect crops from pests in the agricultural system. Pesticides are chemicals used to deter, eliminate, or control pests, unwanted species of plants, or animals that are causing harm or interfering with the cultivation, manufacturing, storage, transportation, or selling of food, agricultural crops, wood, wood products, or animal feedstuffs or which can be given to animals to keep flies, mites/spider mites, and other pests out of or on their bodies (FAO 1989).

Pesticide residue is described as substances that remain in or on a feed or food product, soil, air, or water after a pesticide has been applied. It contains the parent compound as well as any toxicologically relevant degradation products, metabolites, or impurities. Pesticides are often applied in crop to manage the pest during cropping seasons and non-cropping seasons to regulate the weed in fallow land and those pesticides reach the soil, and water. The non-judicious use of pesticides caused hazard and toxicity to non-target organism (birds) and environmental pollution. The effect of pesticides on soil microorganisms is determined by the physical and chemical characteristics of the soil, as well as the chemical composition and concentration of the pesticides. Microbes have been shown to be able to thrive in the presence of pesticides and use the pesticide molecules as carbon and energy sources in numerous studies. Pollen and nectar poisoned by systemic insecticides (pesticide moves inside the plant via xylem) can kill bees and other pollinators. Pesticide usage over time can lead to bioaccumulation and biomagnification in plants and other species. Pesticides that disrupt microorganisms' activities can have an effect on the nutrient cycle and soil nutritional quality, resulting in severe ecological imbalance (Handa et al. 1999).

The microbial population of 1 g of soil during a counting is a barometer of a country's agricultural prosperity. The total mass of microflora and fauna underneath the soil is 20 times that of the entire world's human population. In one gramme of healthy soil, there are one million to 100 million bacteria involved in organic matter breakdown, 0.15–0.5 mg of fungal hyphae, 10,000–100,000 protozoa, a few to several hundred microarthropods, 15–500 nematodes, and a couple of earthworms (Lavelle et al. 2001). Microbial activity (primarily bacteria and fungi) aids in the breakdown of soil organic matter and the management of soil aggregates, while other soil components help to maintain proper number of bacteria and fungi through prey–predator encounters, assisting in the recycling and preservation of basic nutrients.

These soil food cycle components are in harmony and are masterfully crafted in interdependent relationships. The structure and performance of the soil food cycle, i.e. the number, operation, and community structure, serve as a key indicator of ecosystem health. Directly monitoring the active and total biomass of each organism group can aid in detecting the dynamics of change that lead to ecosystem harm.

Once pesticides are applied, they dissipate in the soil, water, and environment and persist for a long time or even year after year and have negative impacts on microbial populations. As a result of the decrease in microbe numbers, the food chain conducted by a group is disrupted, as are the components that depend on it. Owing to the loss of soil organic matter, most microbial groups undergo a series of modifications, resulting in altered predator–prey modules, which cause changes in soil aggregation, soil chemistry, pH, and structure. Over the course of a few decades, the soil becomes barren due to a lack of organic matter to support microorganism growth and development (Chowdhury et al. 2008).

24.2 Recent Trend of Pesticides in India

Chemicals such as insecticides, herbicides, or fungicides are commonly used for the control of various pests in agriculture. There are thousands of pesticides of both biological and chemical origins which are used commonly all over the world to minimise losses of crop production. In India insecticides contribute a higher share in total consumption of pesticides. Both per hectare consumption and total consumption of pesticides increase significantly after 2009–2010 (Fig. 24.1).

Pesticide intake per hectare in 2014–2015 was 0.29 kg ha^{-1}, which is approximately 50% higher than the consumption in 2009–2010. Due to the rising cost of manual labour for weed control, herbicides play an important role in the increased use of pesticides (FICCI 2015). Punjab had the highest per hectare intake in 2016–2017 (0.74 kg), followed by Haryana (0.62 kg) and Maharashtra (0.62 kg) (0.57 kg). Pesticide consumption per hectare in India is 0.69 kg on average. When compared to other countries such as China (13.06 kg ha^{-1}), Japan (11.85 kg ha^{-1}),

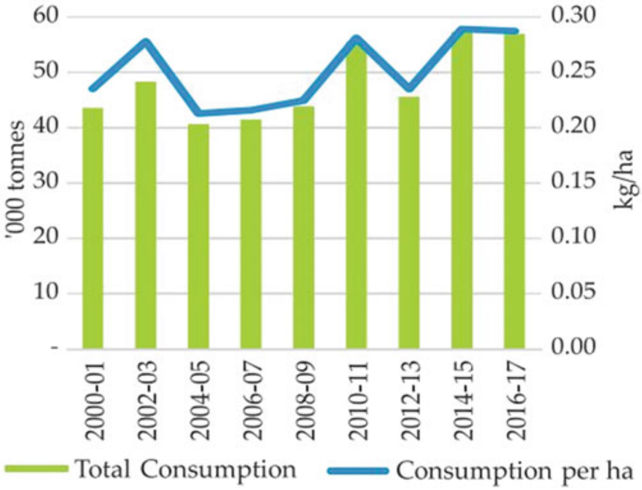

Fig. 24.1 Pesticide (technical grade) consumption in India. (Source*:* Data from Ministry of Chemicals and Fertilizers, Govt. of India)

Brazil (4.57 kg ha^{-1}), and other Latin American countries, this is significantly lower (FAOSTAT 2017).

24.3 Pesticide Production Scenario

In India, insecticides are preceded by fungicides, herbicides, and rodenticides in order of development (Fig. 24.2).

The production share of insecticides lower down from more than 70% in the year 2003–2004 to 39% in the year 2016–2017. The shares of other groups of pesticides such as herbicides, fungicides, and rodenticides grow over a period of time. The increase in the production of fungicides is mainly due to increased use in vegetables and fruits.

24.4 Trade in Agro-chemicals

In the year 2016–2017, 377.76 thousand tonnes of pesticides were exported from India in which fungicide contributes the largest share of 45.94%, followed by herbicides with a share of 28.19% (Fig. 24.3).

Mancozeb, cypermethrin, sulphur, acephate, and chlorpyrifos were the top five pesticides exported in 2016–2017, according to the Central Board of Excise and Customs (CBEC), while glyphosate and atrazine were the top two imported items.

Brazil, the USA, and France are the major countries where pesticides were exported from India (Table 24.1), while China and Germany were major exporters to India.

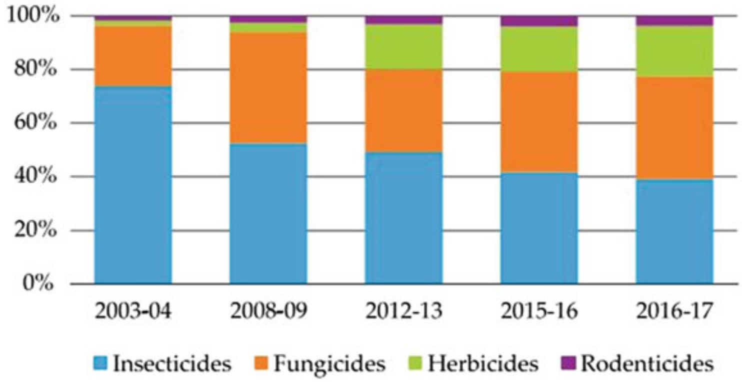

Fig. 24.2 Share of different groups of pesticides (technical grade) in terms of production. (Source: Ministry of Chemicals and Fertilizers, Govt. of India)

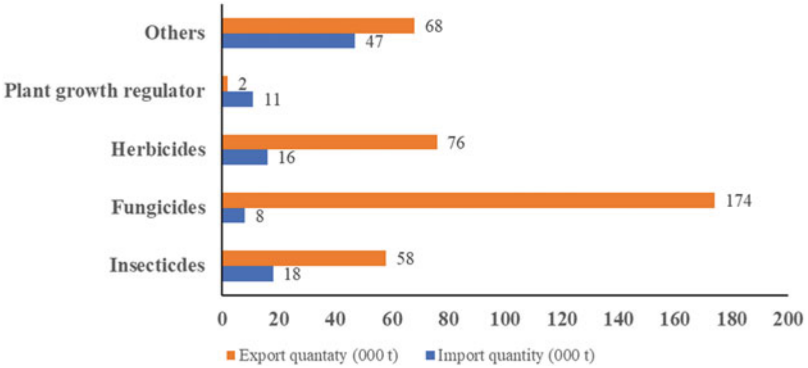

Fig. 24.3 Export and import of major pesticides in India for the year 2016–2017. (Source: DGCI&S, Ministry of Commerce and Industry taken from Subash et al. 2017)

Table 24.1 Major import and export countries for pesticide trade in 2016–2017 (tonnes)

	Country	Insecticides	Fungicides	Herbicides
Export	Brazil	9437.61	42,898.27	20,457.02
	USA	3275.35	8307.82	6095.06
	France	–	7954.77	–
Import	China	11,095.18	2220.28	15,243.93
	Germany	1065.93	1523.81	–
	Japan	–	–	2428.02
	Israel	–	–	4732.66

Source: DGCI&S, Ministry of Commerce and Industry, Govt. of India, taken from Subash et al. (2017)

24.5 Effect of Insecticides on Microbes

In plant protection perspective, insecticides are widely used in agriculture. Due to their xenobiotic properties, the growth of soil microbes and their related soil bioremediation can be negatively impacted by pesticides. Insecticide-contaminated soils are found to inhibit nitrogen-fixing and phosphorus-solubilising microorganisms. Recent studies show that certain pesticides impair plant-to-plant molecular interactions with N-fixing rhizobacteria, thereby retarding the essential biological nitrogen fixation cycle. Similarly, several studies have shown that insecticides suppress soil enzyme activity, which is a key indicator of soil health. Several biochemical reactions can also be affected by pesticides such as mineralisation of organic matter, nitrification, denitrification, ammonification, methanogenesis, etc. On the other hand, a few studies show some positive effects of chemicals applied on soil health.

Pesticides undergo a sequence of degradation, transport, and adsorption/desorption processes in soil, which are influenced by the pesticide's chemical composition (Laabs et al. 2007) and soil properties (Shixian et al. 2018). Interaction of pesticides with soil microbes and their metabolic activities influence the physiological and biochemical behaviour of the microbes (Singh et al. 2006). Microbial biomass is a key indicator of microbial activity and provides a direct measure of the association between microbial activities and the transformation of nutrients and further ecological processes (Schultz et al. 2008). In general, a decline in soil respiration represents a decrease in microbial biomass (Klose et al. 2004) or an increase in respiration (Haney et al. 2000). Some microbial groups are able to replicate using applied pesticides as a source of energy and nutrients, whereas the pesticide may be detrimental to other species (Johnson et al. 2001). The use of pesticides can indeed suppress or destroy certain groups of microorganisms and outnumber other groups by eliminating them from competition. Various positive and negative effects of insecticides on microbes are summarised in Table 24.2.

24.6 Effect of Herbicides on Microbes

Use of herbicides is a common practice all over the world to control unwanted plants in cropped as well as non-cropped areas. Herbicides that were used onto the surface of soil are more likely to influence the growth of microflora as well as micro-fauna. Due to excessive addition of herbicides in the soil, qualitative as well as quantitative alteration in terms of microbial population as well as their enzymatic activities may occur (Min et al. 2002; Saeki et al. 2004). Application of herbicides may also kill the sensitive species of bacteria, fungi, and protozoa that compete with the disease-causing microorganisms, leading to upsetting balance between harmful and beneficial microorganisms. This might lead to a rise of a problem and give opportunities to the pathogens to infect the main crops (Kalia et al. 2004). It is well known in the literature that some microorganisms degrade herbicides leading to stimulated growth of microorganism, whereas some of the other microorganisms were adversely affected in terms of their growth and population depending on the rate of application and type of herbicides used in the field and also on microorganism species and environmental conditions (Sebiomo et al. 2011; Zain et al. 2013).

Many researchers looked into the impact of various types of herbicides on different types of microbes (Adhikary et al. 2014). The effects of three widely used herbicides (pendimethalin, oxyfluorfen, and propaquizafop) on soil microbial species in chilli (total bacteria, fungi, and actinomycetes) were studies and found that herbicide treatments inhibited the production of all three microbial populations in the soil, with the degree of inhibition varying depending on the herbicide used during chilli growth. From the start of the effect until 15 days after application, there was a growing pattern of inhibition on microbial population growth.

Herbicides (paraquat, glyphosate, glufosinate-ammonium, and metsulfuron-methyl) have an impact on microbial population growth, with the degree of inhibition being strongly linked to the rates at which they are applied in oil palm plantations. To bacteria and actinomycetes, paraquat had the greatest inhibitory effect, while glyphosate had the greatest effect on fungi, and metsulfuron-methyl

Table 24.2 Effect of insecticides on microbes

Sl. no.	Insecticides	Microbes	Impact	References
1.	Chlorpyrifos, methylpyrimifos, profenofos	Nitrogen-fixing bacteria, denitrifying bacteria, and nitrifying bacteria	Decreased beneficial microorganism populations	Martinez-Toledo et al. (1992)
2.	Fenvalerate	*Azotobacter* *Azospirillum brasilense* *Azospirillum lipoferum*	Decreased respiration rate and protein contents of diazotrophs	Omar et al. (1992)
3.	Profenofos	Soil fungi, *Penicillium chrysogenum*	Reduction in total-N in fungi *P. chrysogenum*	Moharram et al. (1994)
4.	Carbofuran	Methanotrophs	Carbofuran stimulated the proliferation of methanotrophs	Kumaraswamy et al. (1998)
5.	Endosulfan, monocrotophos, and deltamethrin	Entomopathogenic microorganisms *Beauveria bassiana*, *Metarhizium anisopliae*, and *Sporothrix insectorum*	Reduced the production of conidia and vegetative growth of entomopathogenic fungi	Filho et al. (2001)
6.	Carbofuran	Soil microflora	Adversely affected soil microorganisms	Kalam et al. (2001)
7.	Lindane and dieldrin	*Nitrosomonas*, *Nitrobacter*, and *Thiobacillus*	Toxic	Odokuma et al. (2004)
8.	DDT	Soil algae	A decrease in the diversity of soil algal forms was observed, as well as a decrease in the amount of viable soil algae	Mallavarapu (2002)
9.	Monocrotophos, lindane, dichlorvos, endosulfan, chlorpyrifos, malathion	*Gluconacetobacter diazotrophicus*	May affect the cell morphology and produced pleomorphic cells in large number	Madhaiyan et al. (2006)
10.	Acetamiprid	*Escherichia coli*, *Pseudomonas*, and *Bacillus subtilis*	Stress enzymes in microbes: *Superoxide dismutase*, *catalase*, and *ATPase* were all negatively affected	Yao et al. (2006)
11.	Methamidophos	Soil microorganism	Increase in population of some microbes but decrease in total biomass	Wang et al. (2006)
12.	DDT, methyl parathion	Rhizobium	Interfere with legume–rhizobium chemical	Rockets (2007)

(continued)

Table 24.2 (continued)

Sl. no.	Insecticides	Microbes	Impact	References
			signalling which results in reduced nitrogen fixation	
13.	Cypermethrin	Bacteria and fungi	In the cucumber phyllosphere, there was a rise in bacterial biomass and a decline in fungal biomass, as well as a decrease in the ratio of gram-positive to gram-negative bacteria	Zhang et al. (2008)

had the least inhibitory effect. Glufosinate ammonium and metsulfuron methyl also had similar effects (Zain et al. 2013).

Another study showed the effect of 2,4-dichlorophenoxyaceticacid (2,4-D) and 2,4,5-trichlorophenoxyaceticacid (2,4,5-T) on respiration of *Azotobacter* and concluded that both inhibited the respiration of *Azotobacter* but inhibition was more by 2,4,5-T in comparison to 2,4-D (Magee et al. 1955).

24.7 Pesticidal Impact on Processes of Decomposition

The decomposition of organic matter in soil is an integral portion of nutrient cycling method in soil. During spraying pesticides get in contact with crop residues in the soil. The nonselective preplant herbicides like, glyphosate and paraquat are extensively used, which contribute to slow decomposition of various plant materials. There is inhibition of decomposition of paraquat-treated cellulose thread, but very negligible decomposition of paraquat-treated soil was examined (Grossbard et al. 1978). Further studies on barley and wheat straw also revealed that when straws were kept on soil surface, greater inhibition occurs with application of paraquat (Grossbard et al. 1981). Although in some experiments glyphosate has shown its inhibitory effect, its effect are inconsistent too (Grossbard et al. 1981); (Hendrix et al. 1985; House GJ et al. 1987). Collectively, these studies indicated that the recommended doses of paraquat and glyphosate can hinder the crop residue decomposition. When paraquat and glyphosate were sprayed on crop residues, they appeared to improve decomposition, but their overall results are mixed. Decomposition was reduced more when residues were left on the soil surface than when they were added. The effects of those herbicides on crop residue decomposition were apparently due to high herbicide concentrations remaining after spraying. Paraquat and glyphosate concentrations that inhibit microorganisms in pure culture were typically higher than those present in soil after field application (Grossbard et al. 1979; Grossbard et al. 1985), and both herbicides used in the soil have negligible harmful effects on microbial species (Roslycky 1982). Both paraquat and glyphosate are highly adsorbed in soil, which may explain why herbicides applied to soil are ineffective. Other herbicides, such as 2,4-D and 2,4,5-T (Gottschalk et al. 1979; Fletcher et al. 1986; Sikka et al. 1982), trifluralin, and its metabolites (Boyette et al. 1988), tend to have little effect on cellulose or plant residue decomposition, at least at high concentrations. However, the effects of other recently established herbicide classes, such as sulfonylurea herbicides, which inhibit amino acid synthesis in microorganisms and are similar to glyphosate, have yet to be evaluated.

Though the reduction rates of crop residue decomposition had not yet been assessed fundamentally, some of the effects can be drawn from this. The effects of paraquat and glyphosate will be more in without-tilled crop residue than in other different residue management systems because of surface retention of different crop residues which increases the use of those herbicides. Greater amount of surface pesticide residues may interfere with plant growth as well as weed control, and these lead to increased inhibition of decomposition process. The residence time of straw or other crop residues on the soil surface is determined by additional crop residue coverage in cropping systems. While herbicides can temporarily delay the decomposition process, there is no evidence that they have any long-term effects. Furthermore, there is no evidence that the use of these herbicides affects long-term nutrient turnover in crop residues.

24.8 Pesticidal Impact on Nutrient Cycling

24.8.1 Effects on Nitrogen Transformations

One of the most crucial criteria for crop production is the management of soil N. The conversion of plant nitrogen found in crop residues and soil organic matter to NH_4 and then to NO_3 is known as mineralisation, and it accounts for 40–60% of crop nitrogen, with fertiliser N accounting for the remainder. The residual nitrogen in crop residues was returned to the soil, where it was gradually re-mineralised as the residues decomposed. A wide variety of soil microorganisms participate in the mineralisation process, but only a few species transform NH_4 to NO_3^-. Many studies have been conducted to determine the effects of pesticides on nitrogen mineralisation, and it is clear that the contrast of NO_3^- and NH_4 nitrogen produced in pesticide-treated soils to that produced in untreated soils is the most important factor. The capacity for N production in a soil is influenced by the C/N ratio of soil organic matter and crop residues, as well as the size of the microbial biomass.

Goring and Laskowski (1982) examined the impact of insecticides, herbicides, fungicides, and nematicides on N transformations in soil and found that the majority of pesticides have a marginal effect, inhibiting nitrification and mineralisation by less than 25%. It was observed that most of the pesticides inhibit those natural processes only above the recommended rates for field application. Soil fumigants, e.g. chloropicrin or methyl bromide, particularly have important effects on nitrogen mineralisation and nitrification (Martin 1972). Initially, decreased populations of all microorganisms and N mineralisation were observed. Since fumigated soils get recolonised, nitrogen mineralisation process enhances and progressively may exceed than that of non-fumigated soil. However, long after fumigation nitrification may get suppressed, thus newer systemic nematicides and insecticides replaced soil fumigants to a large extent. There was no declination in microbial biomass or soil nitrogen mineralised in laboratory and field experiments using nematicides such as fenamiphos and oxamyl (Tu 1980; Ross et al. 1984, 1985). Fensulfothion, but not carbofuran, inhibited the populations of various fungi and bacteria. Moreover Tu (1972) reported that neither chemical inhibits mineralisation or nitrification. Dithiocarbamate fungicides may inhibit nitrogen mineralisation under certain conditions. Single pesticide applications have varying effects on nitrogen availability, but repeated pesticide applications or single applications above the recommended levels will reduce both ammonification and nitrification (Jaques et al. 1959; Dubey et al. 1970; Mazur et al. 1975). Maximum 10 ppm of those fungicides can cause reductions in fungal and bacterial populations, and subsequently increasing rates inhibit soil respiration (Tu 1980) and glucose metabolism (Boyette et al. 1988), indicating that those compounds are relatively nonselective towards microbes. Since certain fungicides are relatively nonpersistent in soil and microbial activity, soil nitrogen mineralisation ability will easily recover following their degradation. Corke et al. (1970) discovered that certain pesticide-degraded products had slight effects on nitrogen transformations, such as a 2- to 4-day lag for nitrification when low concentrations of 3,4-dichloroaniline were present. This is a popular phenylamide herbicide and substituted urea degradation product.

When applied at the same concentrations as the metabolites of the herbicides, the parent herbicides had no effect. The metabolites of insecticides including terbufos and phorate, such as sulfoxide and sulfone, reduced nitrification in soil to a lesser degree than the parent compounds (Tu 1980). Other pesticide metabolites have little attention towards mineralisation. The effect of pesticides on microbial fertiliser transformations has yet to be thoroughly investigated. Marsh (1985) investigated the impact of seven herbicides on nitrogen and phosphorus transformations in both fertilised (triple superphosphate and NH_4NO_3) and unfertilised soil. Asulam not only avoided nitrification in fertilised soil, but it also greatly reduced nitrogen mineralisation. While glyphosate, chloridazon, paraquat, and isoproturon decreased phosphorus availability, the effects were very subtle and not agronomically important. In general, the above pesticides tend to have a much lower inhibitory effect on the nitrification process than commercially available nitrification inhibitors (Bundy et al. 1973; Turner 1979), although some direct comparisons have been made. The soil enzyme urease converts urea to NH4+, which is a common nitrogen fertiliser. Monuron, fenuron, diuron, linuron, and neburon, among other substituted urea herbicides, inhibited soil urease production (Cervelli et al. 1976). According to one study, conversion of urea to NH4+ was reduced by 8–39% depending on herbicide concentration (2–10 ppm) and soil type (Maria et al. 2013). Mancozeb, a dithiocarbamate fungicide, inhibited urease activity as well. Pesticides that inhibit urease activity could theoretically reduce the conversion of this fertiliser to NO_3^- over time, particularly if used in combination or close proximity to urea treated in the soil. Mild inhibition of the urease enzyme will avoid NH_4^+ toxicity issues on occasion and limit nitrogen losses from NH_4 volatilisation and nitrate leaching. Denitrification has been shown to be inhibited by pesticides when used at higher rates. At low concentrations, the insecticide carbaryl and the herbicide dalapon were found to be inhibitory (Grant et al. 1982; Weeraratna 1980). Later studies by Yeomans et al. (1985, 1987) found that although dalapon's inhibitory effects were not verified, higher rates of metribuzin or dinoseb induced denitrification. Although inhibiting denitrification can help with efficient nitrogen management, these findings showed that herbicides used at recommended rates have a fairly consistent impact on denitrification.

24.8.2 Transformation of Sulphur

The oxidation of elemental sulphur to sulphate and the reduction of sulphite are the most important transformations since sulphate is the main plant-available nutrient. Despite previous assumptions that heterotrophic microorganisms are more essential for nitrification, the oxidation process is carried out by advanced chemoautotrophic bacteria. Due to sulphur deficiency in different parts of the world, pesticides have a significant impact on the sulphur oxidation mechanism (Coleman et al. 1966). Sulphur, which must be oxidised before it can be used by plants, can also be used to address such shortages. Given the importance of sulphur in crop production, the literature includes only a few studies on pesticide effects on sulphur oxidation. The organophosphate group of insecticides had little impact on soil sulphate, while nematicides such as DDVP, carbofuran, and Vorlex reduced sulphur oxidation marginally (Tu 1972; Aristeidis et al. 2020). Paraquat, on the other hand, slows down the process significantly (Tu et al. 1968). Audus (Audus et al. 1970) discovered that when insecticides (DDT, BHC, aldrin, dieldrin, etc.) are applied at field concentrations, they have no effect on sulphur-oxidising bacteria.

24.8.3 Availability of Trace Elements

The solubility of trace elements in soils has been shown to be impaired by soil fumigants (Warcup 1957). Fumigants appear to affect manganese in particular, so steam sterilisation increases toxic levels (Sonneveld et al. 1973). Some pesticides' effects on trace elements have received much less publicity. Smith and Weeraratna (Smith et al. 1974) found that the herbicides simazine and ioxynil increased manganese solubility as well as Mg, Ca, Fe, and Cu solubility in acidic and alkaline soil media.

Wainwright and Pugh (Wainwright et al. 1974) discovered a similar pattern in their research after fungicide treatment in both laboratory and field treated soils. The mechanism of the process is unknown; it may be caused by lysis of dead microorganism cells or by microorganisms solubilising the components.

24.9 Conclusions

The primary aim of agricultural growth is to feed and supply enough food, nutrition, and surplus to the increasing human population while mitigating environmental and ecological harm. Pesticides are regarded as one of the most effective crop protection tools in developing countries. Since pesticides and their derivatives stay in the soil system for such a long time, they pose significant risks to soil health, the soil microbial ecosystem, and human health. Plant defence chemicals have been shown to minimise soil bacteria, fungi, and almost all flora and fauna populations, as well as soil microbial activity, biomass carbon, and nitrogen mineralisation. The use of natural pesticides and bio-pesticides, as well as judicious application of agrochemicals, should be encouraged.

Pesticide use must be limited in order to reduce the negative effects of pesticides on humans and the environment, which necessitates public awareness campaigns among farmers and other stakeholders. Long-term impact of pesticides on soil microbial populations and the soil ecosystem should be researched in detail. Organic pesticides can aid in the preservation of our environment's microbial niche at this early stage of organic agriculture.

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