Int J Seed Spice, 15(1), June, 2025: 33-53 DOI: https://doi.org/10.56093/IJSS.v15i1.3

Pesticide Applications and Their Ecological Footprint: Impact on Nutrient Dynamics and Agronomic Health

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Received: 01 January 2026
Revision: 29 January 2026
Accepted: 23 February 2026

Citation

Tripathi, Kailashpati, Jangir, C.K., Mahatma, M.K., Talaviya, H., Parshant Kaushik, P., Kumar, R., Arya, S., Saini, S. 2025**.** Pesticide applications and their ecological footprint: impact on nutrient dynamics and agronomic health. *Int J Seed Spice.*15 (1): 33-53

DOI

https://doi.org/10.56093/IJSS.v15i1.3

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Abstract

This review provides a compelling examination of the escalating use of pesticides in Indian agriculture, underscoring their profound environmental consequences, particularly regarding soil health and nutrient cycling. Initially modest, pesticide application surged dramatically following the Green Revolution, reaching 266 grams per hectare by 1976, and now represents a staggering 55% of all pesticides utilized. This pervasive reliance raises critical concerns about the persistence of pesticide residues and their environmental fate, involving complex processes such as adsorption, degradation, and transport mechanisms. Notably, despite a significant 27.69% reduction in chemical pesticide use between 1994-1995 and 2001-2002, the risks remain substantial. Research demonstrates that pesticides severely undermine soil fertility and disrupt microbial activity by interfering with essential carbon and nitrogen cycles, altering key enzymatic functions (such as dehydrogenase), and suppressing vital nitrogen-fixing bacteria. For example, glyphosate has been shown to hinder the absorption of crucial micronutrients like iron (Fe) and manganese (Mn), while chlorpyrifos compromises the availability of essential nutrients—such as nitrogen, phosphorus, and potassium (NPK). Furthermore, the availability of zinc (Zn), copper (Cu), and manganese (Mn) is variably affected by other commonly used pesticides, including 2,4-D and endosulfan. To address and mitigate these detrimental effects, this review passionately advocates for the adoption of Integrated Pest Management (IPM) strategies and the transition to organic or bio-based alternatives. While pesticides are undeniably vital for ensuring food security, their judicious and limited application is crucial for safeguarding soil health and promoting sustainable agricultural practices. The time has come to prioritize the health of our ecosystems alongside agricultural productivity, paving the way for a more sustainable future., such as 2,4-D and endosulfan. To lessen these adverse effects and promote decreased toxicity, quicker decomposition, and increased soil biodiversity, the review highlights the importance of Integrated Pest Management (IPM) and the use of organic/bio-based substitutes. Applying pesticides sparingly is essential to preserving soil health and guaranteeing sustainable agricultural production, even though they are vital for food security.

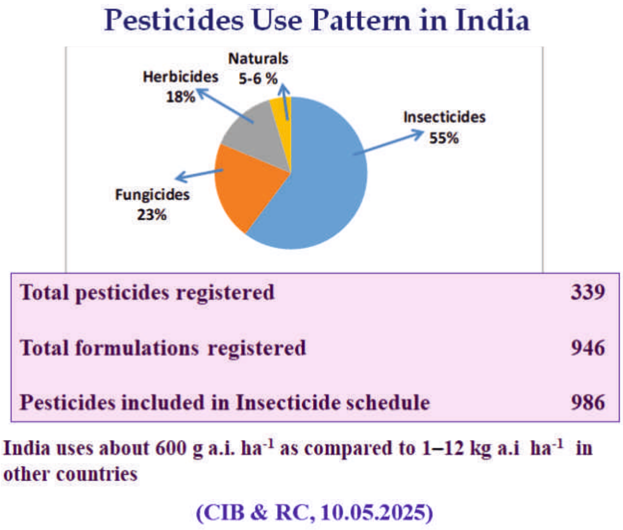
Keywords: Pesticide, Pesticide-nutrient interaction, Nutrient dynamics, Micronutrient

Introduction

As part of effective crop husbandry, Indian farmers have historically utilized various non-chemical methods to minimize crop losses from weeds, diseases, insect pests, and nematodes before the Green Revolution. Before the revolution, two primary approaches to pest management were biological and cultural, while chemical pesticide use for crop protection was almost nonexistent during this period (Patel *et al.*, 2020). After World War II, when DDT was introduced to India to combat malaria, tea and coffee plantations began using pesticides. The first agricultural application of pesticides occurred in 1948 when BHC was used to control locusts, and in 1949, small quantities of BHC and DDT were imported and distributed to farmers. The use of pesticides began to increase significantly when the Indian government launched the "Grow More Food Campaign" during the First Five-Year Plan (1951–1956). Up until 1951, India was primarily dependent on foreign insecticides (www.iari.res.in/files/Publication/Others/ICAR_now_and_ahead).However, when BHC manufacturing facilities were established in Rishitra in 1952 close to Kolkata, it marked the beginning of domestic production. A DDT production facility was established in Delhi in 1954. Initially, India produced 200 tonnes of technical-grade insecticides in 1952, which increased to over 2,800 tonnes by the end of the First Five-Year Plan, resulting in a pesticide application rate of 15 g/ha . As the importance of plant protection for boosting agricultural output became more recognized, the demand for chemical pesticides continued to rise. By 1966, the year high-yielding wheat and rice cultivars were introduced, pesticide use had reached 94 grams per hectare (g/ha). This trend continued, with pesticide consumption climbing to 266 g/ha within the first ten years of introducing these new cultivars. These varieties required substantial applications of fertilizers and pesticides to achieve their high yields. Pesticide usage peaked around 1990–1991 before beginning to decline, with current estimates of India's pesticide consumption per hectare at 0.5 kg, compared to much higher consumption rates in China (17 kg), Japan (12.5 kg), Brazil (4.57), and even some European countries like Germany (3.7 kg) and France (3.7 kg). The UK also uses considerably more, at 2.8 kg per hectare (Committee Reports (prsindia.org), 2023; Acharya *et al.*, 2025 and https://www.worldometers.info/food-agriculture/pesticides-by-country/).

Crop protection practices in India have remained largely the same over the past decade. Currently, the usage of pesticides is comprised of 55% insecticides, 23% herbicides, and 18% fungicides. Additionally, biopesticides account for less than 5% of the total pesticide consumption in the country (Chakraborty *et al.*, 2023).As of March 2025, there are 946 pesticide formulations registered under the act, and 339 pesticides are registered in the act. At the same time, the government also released a list of pesticides banned (46 pesticides banned for manufacture, import and use), restricted use (9 pesticides) and refused registration (18 pesticides) in the country (DPPQS, 2025).

In India, cotton production accounts for 45% of total pesticide use, followed by rice at 23%, soil products at 8%, and grains, pulses, oilseeds, and millets at 6-7%. Approximately 80000 tonnes of pesticides are applied in agriculture each year. The highest pesticide use is observed in the Indian states of Haryana, Punjab, and Uttar Pradesh, which combined used 45,000 tonnes of specialist-grade pesticides in 2000-01. This increased consumption has led to soil fertility depletion and reduced sustainable yield production. However, with growing awareness of the adverse effects of excessive pesticide use on the environment, the implementation of Integrated Pest Management (IPM) practices has resulted in a 27.69% reduction in chemical pesticide use, decreasing from 66,360 tonnes in 1994-95 to 43,590 tonnes in 2001-02 (Arora *et al.*, 2019). As of now, the Indian population is approximately 1.4 billion and is projected to reach 1.7 billion by 2050. Food grain production has grown substantially, from around 50 million tonnes in 1950-51 to 332.3 million tonnes in 2024-25. To meet the target of approximately 355 million tonnes by 2030, an additional 2.4 million tonnes will need to be produced. Pests and diseases currently cause an average loss of around 20-25% of total food production in India. The per capita pesticide consumption in India is 0.6 kg/ha, which is low compared to other countries. Pesticides applied to

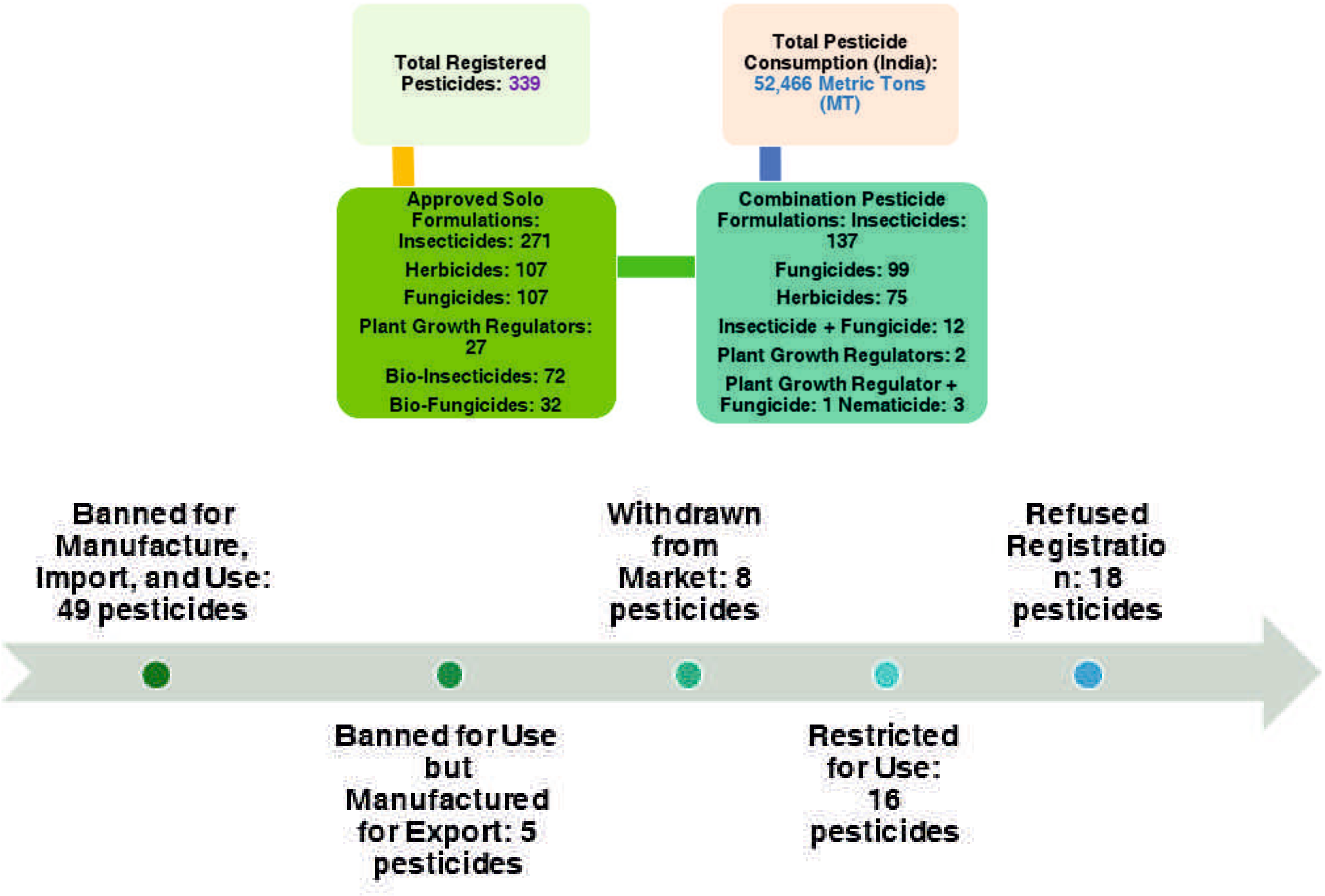


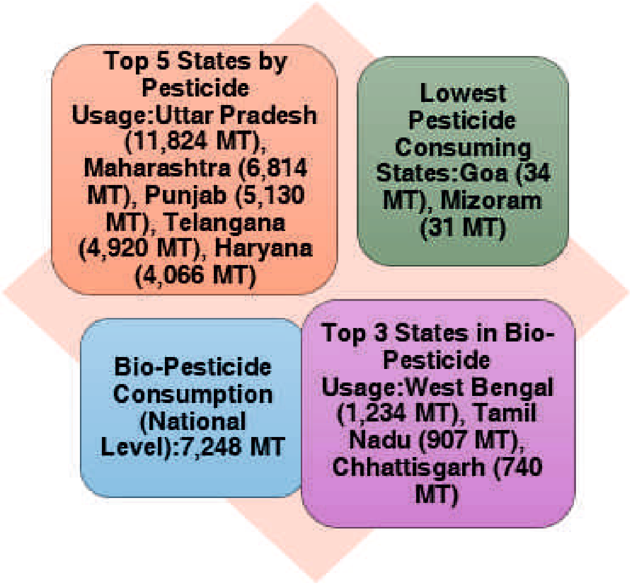
Total pesticides registered	339
Total formulations registered	946
Pesticides included in Insecticide schedule	986

India uses about 600 g a.i. ha^{-1} as compared to 1–12 kg a.i ha^{-1} in other countries

(CIB & RC, 10.05.2025)

Fig.1: Pesticide use pattern in India





Scheme: Pesticide consumption in India

crops are immobilized through sorption using various methods and factors (Tiryaki and Temur, 2010).

Pesticide environmental dynamics

Environment

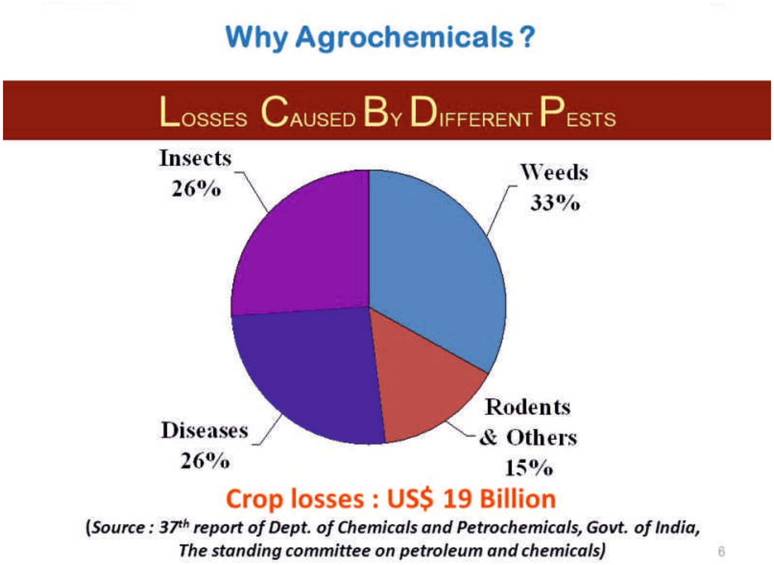
The environment is defined as the whole physical and biological system surrounding man and other organisms along with a range of factors influencing them. Soil, air, water, light, temperature, and so forth are the factors. These are called abiotic factors. Besides, biotic factors which include all forms of life like plants, animals, microorganisms etc.

Physical Constituent of the environment mainly determines the type of the habitat or living conditions of the human population.

(i) Atmosphere (gaseous or air)

(ii) Hydrosphere (liquid or water)

(iii) Lithosphere (solid, soil)



(*Source : 37th report of Dept. of Chemicals and Petrochemicals, Govt. of India, The standing committee on petroleum and chemicals)*

Fig. 2: Losses caused by different pest

The three major states of matter that make up the environment are represented by the three components

Pesticides in soil

1. Deliberate application
2. Accidental
    - Spay drift
    - Burial of container
    - Equipment washing
    - Washing from plant surface
    - Pesticide vapors dissolved in rain
    - Plant residue

Pesticides in soil occur in two forms:

1. Free
    - Adsorption
    - Degradation

Transport :(Soil to air – Volatilization) (Soil to water – Runoff and leaching) (Soil to biota –Uptake) (Movement in soil –Diffusion and mass flow)

Bound

Adsorption

Adsorption refers to the distribution of pesticide molecules between the solid phase (soil) and the liquid phase (soil solution). It is a surface phenomenon that removes compounds from the bulk phase, thereby influencing their behaviour in the soil environment. Adsorption can decrease through mechanisms such as volatility and plant uptake, microbial degradation, transport through roots and the vadose zone, and dispersion in groundwater. On the other hand, adsorption can increase via transport through erosion and runoff. Additionally, chemical degradation may be enhanced through surface-catalysed reactions.

Mechanism of Pesticide Sorption

For effective pesticide accumulation, there must be some form of attraction between the solute (pesticide) and the sorbent (soil). Soil colloids may have partial or full charges that can be temporary or permanent. Similarly, pesticide molecules can be ionic or can dissociate in the soil, resulting in ionic compounds or partial charges.

Physical Adsorption: This type of adsorption occurs due to dipole-dipole interactions, polarization, or

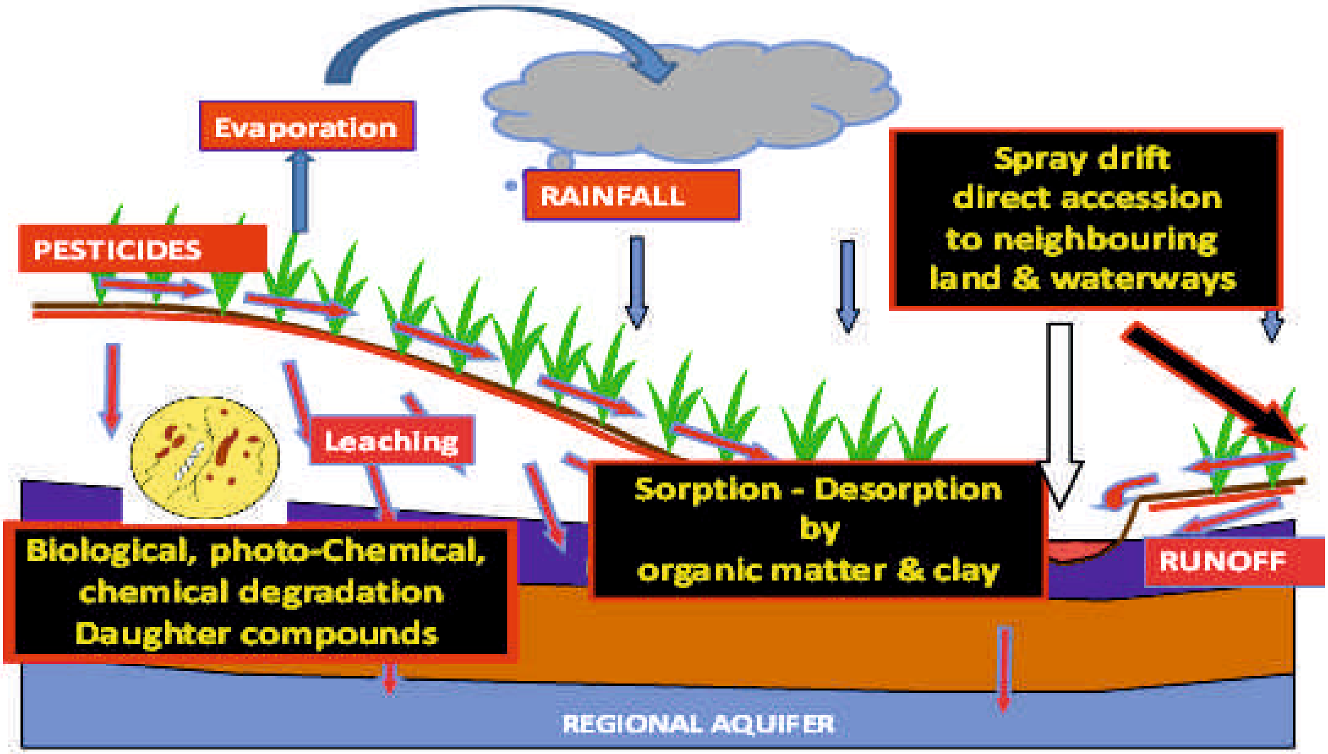


Fig 3. Pesticides in soil

induced dipole interactions. Physical adsorption is generally reversible and occurs with non-ionic pesticides, exhibiting low binding strength.

Chemical Adsorption: This process is driven by Coulombic forces, leading to bond formation between the adsorbent and adsorbate. It typically involves cationic and anionic pesticides, resulting in high binding strengths (Tiryaki and Temur, 2010).

Pesticide Sorption Mechanisms

Van der Waals Attraction: These forces play a role in the adsorption of non-ionic molecules. They result from short-range dipole-dipole interactions. In larger molecules, the cumulative Van der Waals forces between the atoms of the adsorbent and adsorbate create strong attraction.

Hydrogen Bonding: This is a specific type of dipole-dipole interaction where a hydrogen atom acts as a bridge between two electronegative atoms. One atom is bonded covalently, while the other is held by electrostatic forces. Protonation and hydrogen bonding are similar processes, with protonation involving complete charge transfer and hydrogen bonding involving partial charge transfer.

Hydrophobic Bonding: Non-polar pesticides or compounds, often with significant non-polar regions relative to their polar regions, are likely to adsorb onto the hydrophobic regions of soil. On hydrophobic surfaces, water molecules in the system do not compete with non-polar molecules for adsorption. This type of interaction is a significant factor in the strong adsorption of many pesticides by soil organic matter.

Charge Transfer: Charge transfer interactions occur only over short distances between the interacting species. The formation of charge transfer complexes involves electrostatic attraction when electrons move from an electron-rich donor to an electron-deficient acceptor ($\pi-\pi$ Electron Donor–Acceptor Interactions). This mechanism has been suggested to explain the adsorption of triazines on soil organic matter.

Ion Exchange: This occurs for pesticides that are cationic or can become positively charged through protonation. For instance, the adsorption of pesticides like paraquat and diaquat via cation exchange involves -COOH and phenolic-OH groups associated with soil organic matter. The cationic adsorption mechanism can also account for the adsorption of less basic pesticides, such as triazines, onto organic matter.

Ligand Exchange: In this mechanism, the adsorbent molecule replaces one or more ligands during adsorption. This process requires that the adsorbent molecule is a more potent chelating agent than the ligands it replaces. Partially chelated transition metals may act as adsorption sites in ligand exchange (Tiryaki and Temur, 2010).

Factors Affecting Sorption

Properties of Soil: Various soil parameters, such as organic matter content, clay content, cation exchange capacity (CEC), pH, moisture, exchangeable cations, temperature, and other environmental conditions, influence sorption

Properties of Pesticide: Factors such as the pesticide's acidity (pKa), basicity (pKb), solubility, charge distribution, molecular polarity, size, and concentration in the solvent affect its sorption behaviour.

Properties of Soil

Organic Matter: This has the most significant impact on pesticide sorption. Organic matter contains polar groups such as acids, amines, amides, and phenols, as well as hydrophobic fractions like lipids. Therefore, it can serve as a site for adsorption for both ionic and non-ionic compounds, as multiple sorption mechanisms are possible. In general, pesticide sorption correlates directly with the soil's organic matter or organic carbon content. However, recent studies indicate that it is not just the total organic carbon content that matters; the chemical nature of the organic carbon also significantly affects pesticide adsorption.

Clays: The clay fraction in soil, particularly in soils with low organic carbon content, plays a crucial role in pesticide adsorption. Soils with two-layer clay (non-expandable) are particularly influential in this regard. Effect of pesticide on nutrients

Properties of Pesticide

Functional Groups: The functional groups found in pesticides, such as carbonyl, carboxylic, ester, amide, and phenol, influence their sorption properties. This is because these groups can become ionized or polarized. Additionally, the electronegativity or electropositivity of the atoms adjacent to a functional group can also affect its ionization and polarization.

Dissociation Constant: The dissociation constants (pKa and pKb) of pesticides play a significant role in their ionization. Depending on the pH of the soil, pesticides that produce ions can exhibit different mechanisms of action. Typically, cationic pesticides tend to be more readily absorbed by soil.

Solubility: Pesticides that have high solubility in water tend to remain in water and are poorly sorbed on soil particles; thus, in general, pesticide adsorption is inversely related to their aqueous solubility (Briggs, 1981). Among the factors influencing water solubility are polarity, molecular size, pH, and temperature. Most pesticides are less polar than water, so they tend to accumulate in soil. Pesticides with higher octanol-water partition coefficient (Kow) (hydrophobic) values are more strongly sorbed than the ones that have low Kow values; therefore, Kow constant is directly related to pesticide adsorption (Shiu *et al.*, 1990).

Vapour pressure: Pesticides with low vapour pressure gets easily volatilized and escape in the environment. On the contrary, those with high vapour pressure, depending on their water solubility, will partition themselves in soil and water (low water soluble one will partition in soils, while high water soluble will be mainly available in water phase). Thus, soil moisture content will play an important role in pesticide volatility. Further, volatilization of pesticide is affected by environmental factors like wind speed, temperature, etc.

ndia ranks ninth in global pesticide consumption. Chemical pesticide consumption in India in 2021-2022 was 58720 MT, with 13,175 metric tonnes. Maharashtra leads the states in chemical pesticide use, followed by Uttar Pradesh (11,688 metric tonnes), Telangana (5,090 metric tonnes), and Jammu & Kashmir (4,086.32 metric tonnes) during the years 2022-2023 (Lok Sabha USQ:1069 dated 13 December 2022) (Fig.). Over the past decade (2012-13 to 2021-22). Crop protection patterns in India have not changed significantly over the last decade; we use 55%, 23%, and 18% of insecticides, herbicides, and fungicides, respectively, and biopesticide use in India is less than 5% of total pesticide consumption (Chakraborty *et al.*, 2023). Farmers have been applying more fungicides and herbicides in recent years. In India, the use of biopesticides has steadily increased. It peaked in 2021-2022 at 8,899 metric tonnes, up from 6,148 metric tonnes in 2015-16 (Lok Sabha USQ:1069, dated December 13, 2022). Interestingly, consumption rose significantly to 8,847 metric tonnes in 2020-21. Cotton (44.5%) is the most pesticide-intensive crop grown in India, followed by rice (22.8%), sorghum (8.9%), vegetables (7%), wheat (6.4%), pulses (2.8%), and other crops (7.6%). Cabbage is India's most pesticide-intensive vegetable crop.

Millions of microscopic species, such as bacteria, fungi, and several more, can be found in soil. These microbes are essential to plants' ability to absorb the nutrients from the soil that they require to develop and flourish. Additionally, microorganisms assist soil in controlling water flow, storing water and minerals, and filtering contaminants. Application of nutrients is required since they are essential to crop production and hold the same level of importance as macronutrients. There is very narrow difference between deficiency and toxicity levels, so nutrients should be applied carefully only when crop needs them and after soil test. There is need for application of pesticide at lower dose so it will not affect adversely to nutrient availability. Pesticides are important tools for growing food and ensuring food security. However, they also have negative effects that we cannot ignore. Pesticides can stay in the soil and environment for a long time, impacting living organisms and natural factors. They can harm soil, beneficial microorganisms, other animals, the environment, and human health. This review will discuss how pesticides affect both macro and micronutrients (Zacharia, (2011); Zhong and Cai, (2007).

Effect of pesticide over Macronutrient

Carbon

Indiscriminate use of pesticide disturbs soil microbe as well as soil fertility by disturbing total carbon as well as available carbon. In paddy field different combination of pesticides causing depletion of soil fertility (Arora *et al.*, 2019).

In order to assess the overall microbial activity, soil dehydrogenase enzyme activity has been calculated. Soil microbial biomass carbon is a labile pool or source of nitrogen, phosphorus, and potassium. Continuous

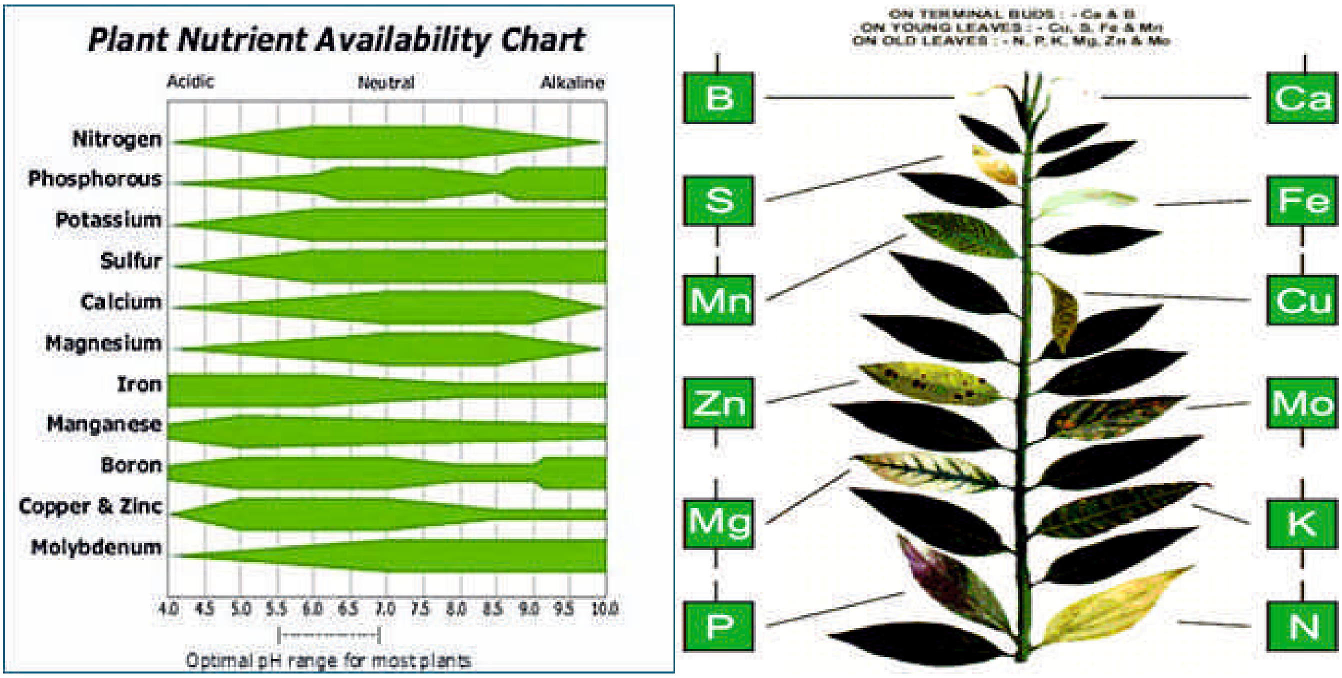


Fig.4: plant nutrient availability chart and nutrient present over distinct parts of plant

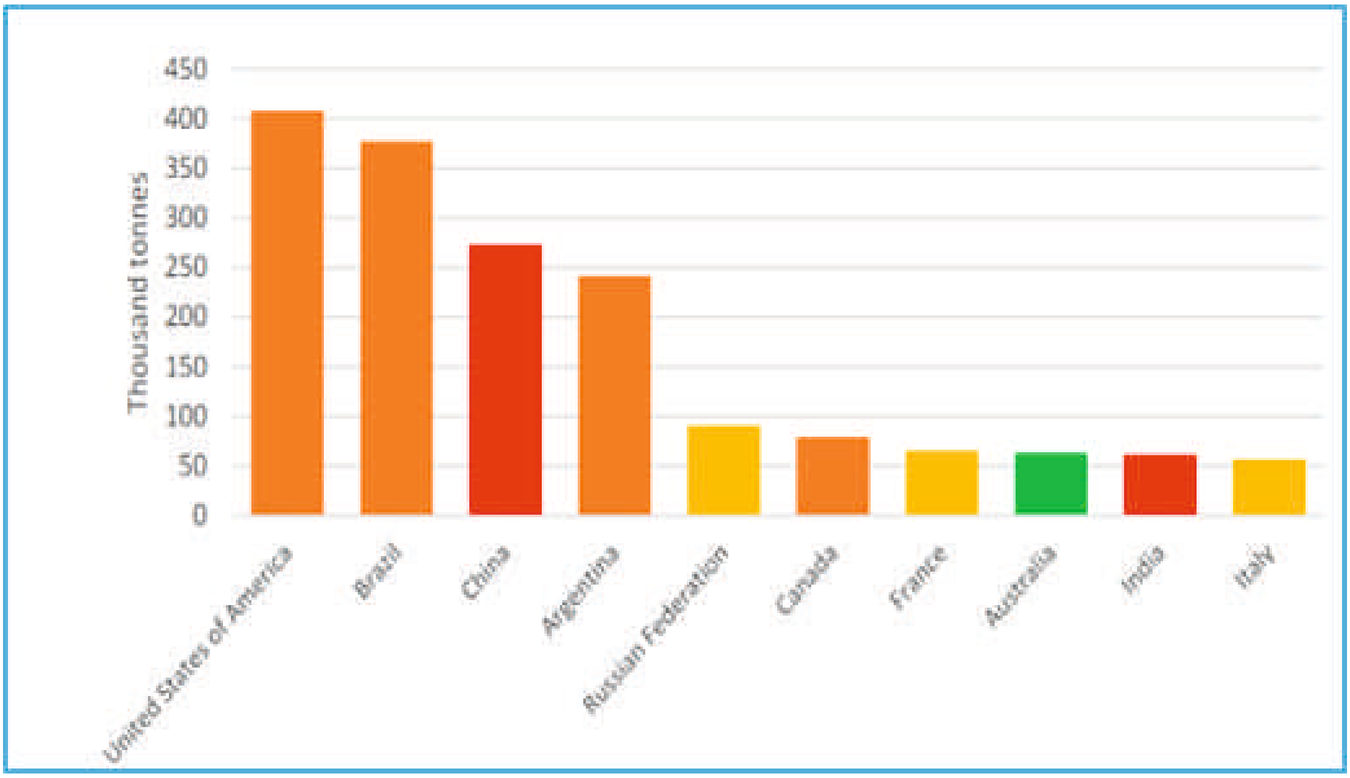


Fig.5: Pesticides use countries (2020)Source: FAO. 2022. FAOSTAT: Pesticides Use. In: FAO. Rome. Cited July 2022. http://www.fao.org/faostat/en/#data/RP

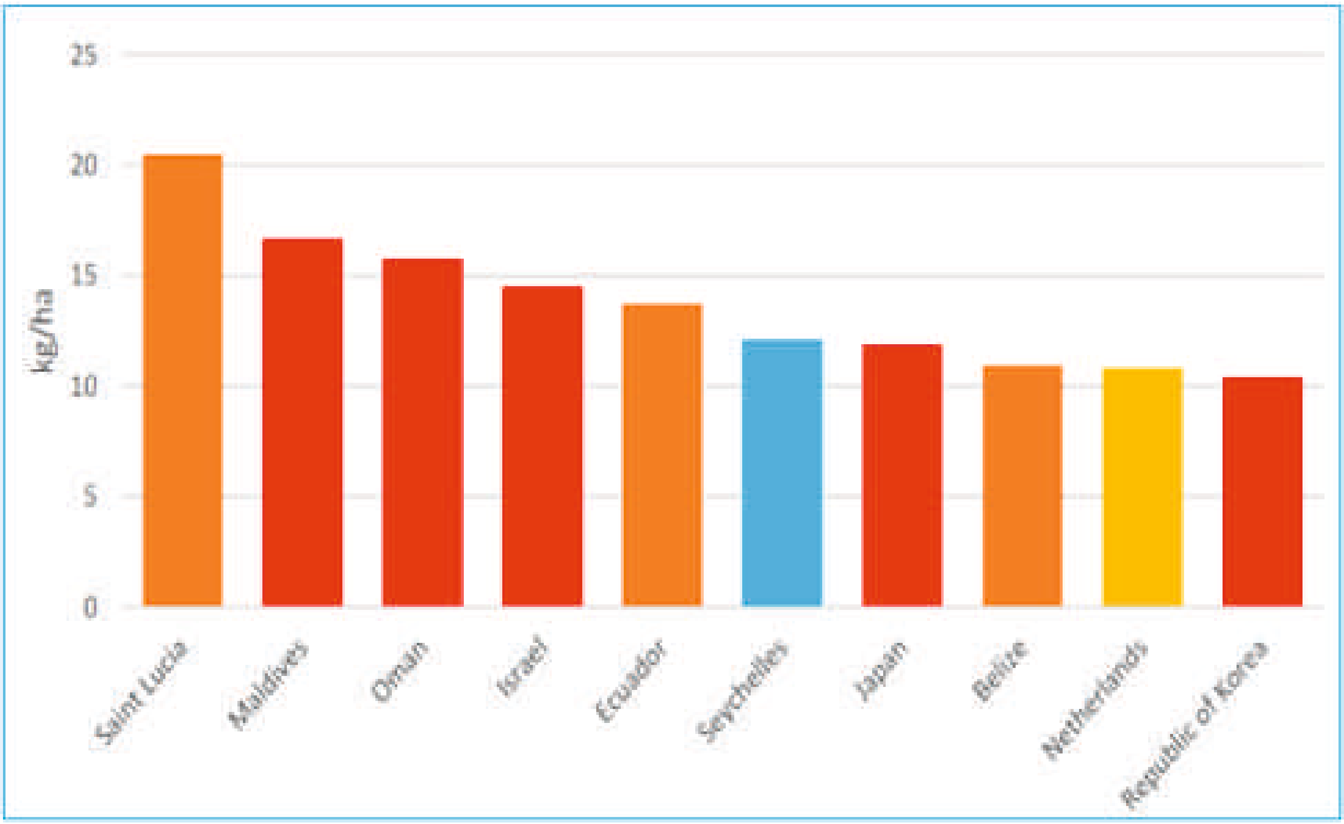
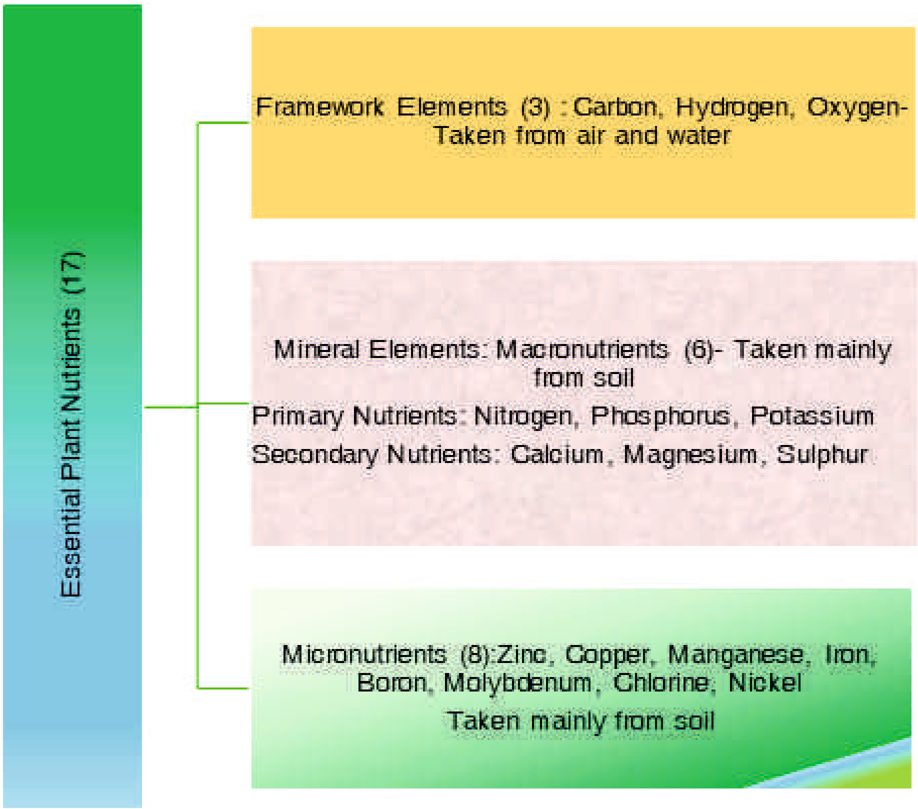


Fig.6 : Pesticides use per ha^{-1} (2020) Source: FAO. 2022. FAOSTAT: Pesticides indicators. In: FAO. Rome. Cited July 2022.http://www.fao.org/faostat/en/#data/EP



use of pesticide could accumulate considerable amount of pesticide. Soil sample taken from 20 locations from rhizospheres soil, where farmer using different type of pesticides. Pesticides reaching the soil might disturb native metabolism or enzymatic activities. Dehydrogenases occur intracellular in all the living microbial cells and these enzymes are linked with microbial respiratory processes. An indication of the total microbial activity of the soils is the presence of dehydrogenase in the soil system. The labile pool of organic materials that serves as a source and a sink of plant nutrients is the soil microbial biomass. It is essential for sustaining soil fertility and nutrient concentration and plays a major part in the cycling of nutrients. Regular pesticide use can build up significant concentrations of pesticides and the byproducts of their breakdown in the soil environment that interfere with soil microorganism activity may have detrimental effects on soil nutrition and have negative ecological repercussions. It was found that the application of 2, 4-D, as opposed to chlorpyriphos, carbofuron, and carbendazim, caused the greatest decrease in soil Dehydrogenase activity (DHA). DHA was found to be reduced (by 58.24%) when 2,4-D was sprayed in comparison to control soil. There was not much variation on soil organic C when pesticides were applied however, maximum decrease in soil total organic C occurred in soils having residues of 2,4-D (Arora *et al.* (2019).

Methamidophos, an organophosphate pesticide, is widely found in soil. Its presence leads to a reduction in fungal biomass and total microbial biomass carbon. However, it increases the biomass and catabolic activity of gram-negative bacteria, while not noticeably affecting gram-positive bacteria under the same conditions. Furthermore, research indicated that the overall genetic diversity of the bacterial community declined due to this chemical stress, as observed through ARDRA patterns (Wang *et al.* 2008).

Similar research has shown that the effects of pesticides decrease organic carbon and total nitrogen from chemical fertilizers, such as ammonium bicarbonate and triadimefon, by 58.5%, 54.8%, and 55.0%, respectively. This reduction is in contrast to soil that has not been polluted by chemicals (Yang *et al.* 2000).

Nitrogen

To determine the impact of atrazine on the microflora and nutrient status of the soil, it was used as a pre-emergence herbicidein sorghum crop. The soil sample were collected from the rhizospheres' layer of plant from herbicide treated plots; it is to be used for all the microbial and biochemical analysis at three stages of crop growth, viz., vegetative growth stage (30DAS), flowering stage (50 DAS) and at harvest (Jadhav et al. (2019). The soil health measure was only temporarily affected by herbicide. There was very little impact of atrazine on the pH, EC, and OC of the soil. It shows that atrazine treatments initially limit microbial growth and have no long-term negative impact on microbial growth in sorghum until the crop is harvested. There were far fewer P solubilizers reported than N fixers (Soumen and Ghosh 2013; Ramesh and Nadanassababady 2005).

A study found that the number of nitrifying bacteria in soil treated with the fungicides dimethomorph and mancozeb significantly decreased when exposed to a dosage of 1500 mg/kg over a period of 28 days. A similar, though somewhat less pronounced effect was observed with insecticides. The herbicides linuron and diazinon were also examined (Cycon and Piotrowska-Seget 2007). Additionally, populations of nitrogen-fixing bacteria were similarly inhibited by these three pesticides at the same dosage and exposure duration. Another study investigated the effects of the fungicide captan at dosage rates ranging from 2.0 to 10.0 kg/ha on nitrogenase activity, aerobic nitrogen-fixing bacteria, and nitrifying bacteria (Martinez-Toledo et al. 1998). Following the prolonged application of several herbicides—including atrazine, butylate, ethalfluralin, imazethapyr, linuron, metolachlor, metribuzin, and trifluralin—to the soil, a slight depression in nitrification was noted. Moreover, treatment with ethalfluralin inhibited the activities of amylase and dehydrogenase in the soil (Tu 1992).

N, P_2O_5 and K_2O

In case of primary nutrient study conducted by sardar *et al.*, (2005) over gangatic alluvial soil to evaluate effect of chlorpyrifos over availability of NPK, when Chlorpyrifos applied with different doses 1,10 and 100 kg/ha, after hydrolysis primary metabolite is 3,5,6-trichloro pyridinol (TCP) and secondary metabolite is 3, 5, 6-trichloro methoxy pyridine (TMP), these metabolites interfere with the nutrient availability. They found significant difference in availability of nitrogen was adversely affected by Chlorpyrifos treatment in compared to control irrespective of incubation period, effect was further intensified with doses, significant decrease in nitrogen and phosphorus content in soil treated with Chlorpyrifos in comparison to control. The reason for inhibitory effect over nitrogen and phosphorus due to its metabolite TCP and TMP, both are affecting nitrogen fixing bacteria and phosphorus solubilizing bacteria, however finally availability of nitrogen and phosphorus recovered significantly after 120 days, in case of potassium there was no significant difference in availability.

N, P_2O_5 and S

Major nutrient availabilities following three years of prolonged use of the herbicides glyphosate and atrazine in soil were reported by Aherobo *et al.* (2020). The nitrate content was approximately 26.68 mg/kg in comparison to the control, with a very slight effect on nitrate status affected by pesticide, indicating herbicide has no effect on the nitrate content of the soil. Three different soils were collected in the case of nitrate at different depths; two of them had been exposed to herbicide for a long time, and the control soil had no history of pesticide application. There was no adverse effect of prolonged herbicide use over NPS, as evidenced by the higher phosphate and sulphate content of the soil compared to the control in the case of maize and carrot.

N & P_2O_5

Propiconazole (1-((2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl) methyl)-1H-1,2,4-triazole) is a broad spectrum triazole fungicide used against various pathogenic fungi. This fungicide is lethal and can persist in the soil for a long time, subsequently affecting soil fertility and microflora diversity. Propiconazole contaminated soil samples were randomly collected at a depth of 15 cm surrounding the paddy root surface.The activity of phosphatase was enhanced in both the soils with propiconazole treatment of 1.0, 5.0 and 10 kg ha^{-1}in comparison with the controls After first week of incubation, the maximum urease and phosphatase activity was noticed in the stimulatory dose (10 kg ha^{-1}) of propiconazole. At higher concentration of propiconazole there is drastic reduction in the enzyme activity was noticed (15 and 20 kg ha^{-1}) for both the soil (Hamada *et al.* (2011).

Red sandy loam and deep black soils with the application of propiconazole (15 and 20.0 kg ha^{-1}), showed a drastic reduction in the bacterial and fungal populations. Lower application doses of 1.0 and 5.0 kg ha^{-1} at one week of incubation enhanced the growth of bacterial and fungal communities when compared with untreated controls. The role of propiconazole, act as a potential agent for the enhancement of soil microbes and enzyme activities in recommended dose of application (Satapute *et al.* (2018).

Nitrogen

Application of glyphosate and propanil also affect the nitrogen availability but in different terms. When only rice straw and chitin was applied in soil there in increase in nitrous oxide production comparison to control because when organic matter amended in soil it causes more denitrification, but application of glyphosate and propanil supress nitrous oxide production in both organic matters amended soil reason behind it was inhibition of denitrifying bacteria by herbicide application, so their herbicide can use as alternative of nitrification inhibitors (kyaw *et al.*2007).

Mechanism of inhibition of Nitrogen fixation

Lu *et al* .,(2020) reported in one study showing effect of pesticide like Chlorpyrifos on mechanism of nitrogen fixation in rice crop, toxic effect of Chlorpyrifos pesticide via reactive oxygen species (ROS) in *Pseudomonas stutzeri* to inhibit nitrogenase activity by reduction in expression of nitrogen fixing gene (Nif A, NifLa), and also reduction of biofilm formation in the microbe by pesticide application because ROS destroy the extracellular polymeric substances, which regulate the biofilm formation in bacteria so there is no biofilm formation .Chlorpyrifos application significantly inhibited up to 0.125 to 8 mg/litre, biofilm measured in OD_{600} decreases from 2.52-1.29 via scanning electron microscope. Chlorpyrifos applied in higher dose significantly decrease in nitrogenase activity.

Effect of Pesticide on soil Micro-nutrients

Its use globally has risen almost 15-fold since 1996, when geneticallyengineered glyphosate-tolerant “Roundup Ready” crops were introduced. In Great Britain in 2014, 1.9 million kgof glyphosate were used

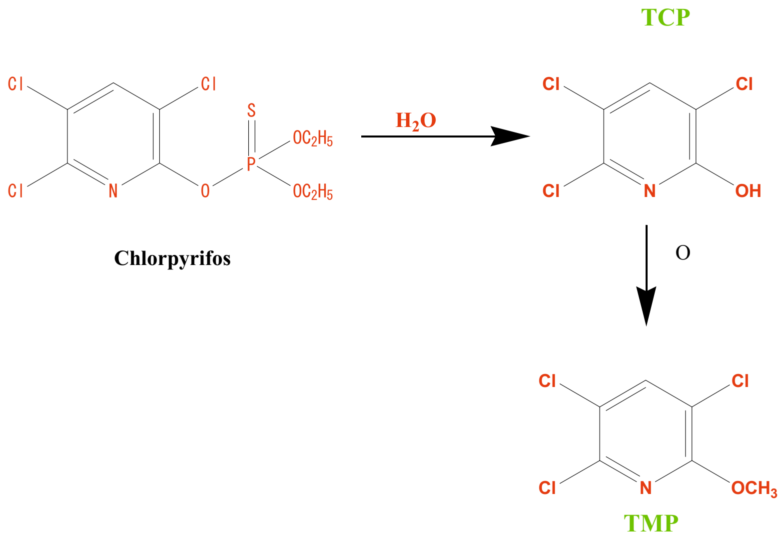


Fig.7: Formation of TMP TCP, a metabolite of chlorpyrifos following its application in soil

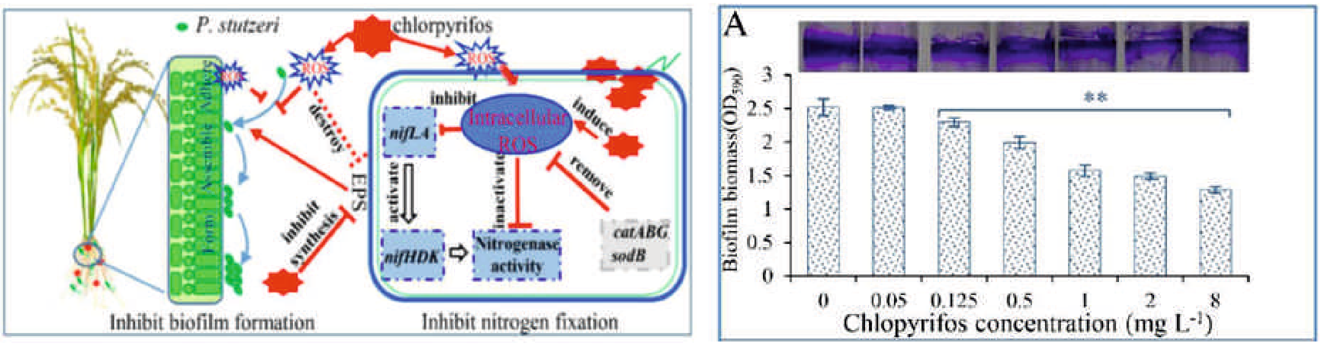


Fig.8: Chlorpyrifos inhibited biofilm formation by *P. stutzeri* A1501 in KN medium. Biofilm formation by *P. stutzeri* A1501 at various chlorpyrifos contents.

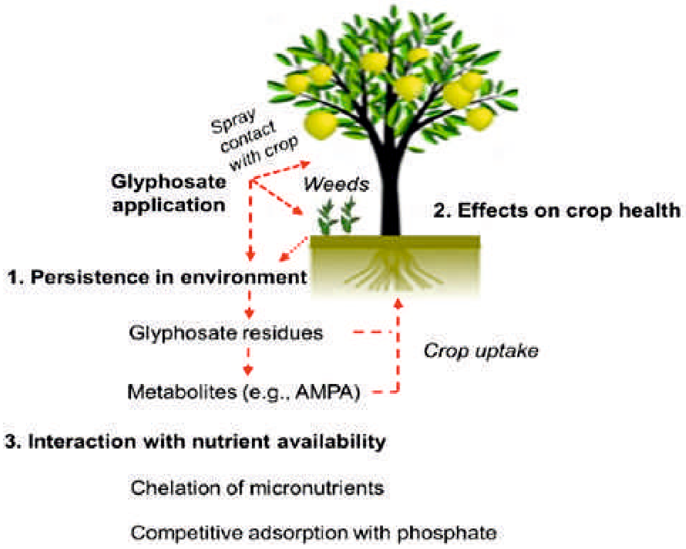


Fig.9: Schematic representation of the potential effects of glyphosate in crop production

Table 1. Effects of Selected Pesticides on Nutrient Dynamics and Soil Properties

Sr. No	Pesticide	Class	Mode of Action	Nutrient Dynamics	Soil Property & Activity	%Increment/Decrement (vs Control)	Remarks	Reference
1	Atrazine	Herbicide	Photosynthesis inhibitor	Nitrogen (N)	Dehydrogenase activity reduced	+13%	Temporary inhibition of microbial growth; effect recovers at harvest	Jadhav *et al.* (2019)
2	Chlorpyrifos	Insecticide	Acetylcholinesterase inhibitor	N, P_2O_5 (decreased), K (no significant change)	Inhibition of N-fixers and P-solubilizers; affects DHA	N ↓18–36%, P_2O_5 ↓50–75%	TCP/TMP metabolites suppress beneficial microbes affecting nutrient availability	Sardar & Kole (2005)
3	Glyphosate	Herbicide	EPSP synthase inhibition	Fe, Mn, Zn, Cu (reduced uptake and transport)	Reduced microbial activity; suppresses biofilm formation	Fe ↓26%, Mn ↓42%, Cu ↓29%	Chelation with cationic micronutrients impairs translocation and bioavailability	Kanissery *et al.* (2019)
4	2,4-D	Herbicide	Synthetic auxin; growth regulator	Zn, Cu, Mn availability increased	Reduction in DHA; mild microbial inhibition	Zn ↑119%, Cu ↑21%, Mn ↑9%	Enhances cationic micronutrient availability; best soil environment outcome	Arora et al. (2019); Paul *et al.* (2013)
5	Endosulfan	Insecticide	GABA-gated chloride channel blocker	Zn, Cu, Mn (immobilized)	Significant reduction in microbial and fungal activity	Zn ↓42%, Cu ↓10%, Mn ↓64%	Creates hostile soil atmosphere with prolonged toxic effects	Paul *et al.* (2013)

6	Propiconazole	Fungicide	Ergosterol biosynthesis inhibition	P and N (variable effect at different doses)	At low doses: enhanced microbe growth; at high: detrimental	Phosphatase ↑ at low dose, ↓ at high	Biphasic effect — stimulatory at recommended dose, suppressive at elevated concentration	Satapute *et al.* (2018)
7	Methamidophos	Insecticide	Acetylcholinesterase inhibitor	Carbon & Microbial Biomass ↓	Genetic diversity of bacteria reduced	MBC ↓10–25%	Reduces fungal biomass; enhances gram-negative bacterial dominance	Wang *et al.* (2008)
8	Dimethomorph, Mancozeb	Fungicide	Multi-site enzyme inhibitor	Nitrogen cycle enzymes inhibited	Nitrification suppressed; DHA reduced	Nitrifiers ↓40–60%	Persistent effects on nitrogen metabolism and enzyme activity	Cycon & Piotrowska - Seget (2007)
9	Captan	Fungicide	Thiophthalimide compound	N-fixers & nitrifiers suppressed	Nitrogenase activity decreased	Nitrogen ↓25–45%	Broad-spectrum suppression of soil microbes involved in N transformation	Martinez - Toledo *et al.* (1998)
10	Atrazine and Glyphosate	Herbicide			no influence on pH, total organic carbon, nitrat		alter the microbial populations with respect to prolonged treatment	Aherobo & Ataikiru (2020).

11	Chlorpyrifos	Insecticide	inhibits acetylcholine esterase	Inhibits nitrogen fixation in rice - vegetated soil		Reduces nitrogenase activity; suppresses nifA and nifH gene expression	Impairs biofilm formation and rhizosphere colonization by Pseudomonas stutzeri A1501	Lu *et al.* (2020)
12	Diuron	Herbicide	Photosystem II inhibitor	Nitrification suppressed	Microbial biomass reduced	Nitrifiers ↓30 –50%	Persistent in soil; inhibits ammonia oxidizers	Cycon & Piotrowska - Seget (2007)
13	Linuron	Herbicide	Photosynthesis inhibitor	N & P cycling disrupted	Enzyme activity (DHA, urease) reduced	DHA ↓40%, Urease ↓25%	Alters microbial respiration and carbon turnover	Niemi *et al.* (2009)
14	Carbofuran	Insecticide	Cholinesterase inhibitor	Organic C & N reduced	Earthworm biomass & microbial diversity ↓	MBC ↓20 – 30%	Toxic to soil fauna and beneficial microbes	Bouwman & Reinecke (1987
15	Mancozeb	Fungicide	Multi -site enzyme inhibitor	Nitrification inhibited	N-fixers and nitrifiers suppressed	N-fixers ↓35%, DHA ↓20%	Alters nitrogenase activity and microbial respiration	Pozo -*et al.* (1994)

16	Glyphosate	Herbicide	EPSP synthase inhibitor	Fe, Mn, Zn, Cu uptake inhibited	Biofilm formation & nitrogenase activity ↓	Fe ↓26%, Mn ↓42%, N -fix ↓50%	Chelates micronutrients; suppresses N - fixation via ROS	Kanissery *et al.* (2019)
17	Propanil	Herbicide	Photosynthesis inhibitor	N_2O production suppressed	Denitrifiers inhibited	N_2O ↓80%	Acts as nitrification inhibitor in organic - amended soils	Kyaw & Toyota (2007)
18	Neonicotinoids	Insecticide	Nicotinic receptor agonists	Soil invertebrate - mediated nutrient cycling ↓	Earthworm activity ↓	Earthworm ↓40%	Disrupts soil structure and nutrient mineralization	Gunstone *et al.* (2021)
19	Pendimethalin	Herbicide	Microtubule assembly inhibitor	Organic C turnover ↓	Microbial biomass ↓	MBC ↓20%	Persistent in soil; affects carbon cycling	Sharma *et al.* (2001)
20	Azoxystrobin	Fungicide	Inhibits mitochondrial respiration (cytochrome bc1 complex)	Alters nutrient cycling (C, N, P); inhibits carbon utilization	Reduces urease, invertase, and phosphatase activity; catalase promoted	Decreases bacterial OTU richness and Shannon index; shifts in *Sphingomonas* and *Amycolatopsis* populations		Wang *et al.* (2020),

21	Dithane M-45	Anionic	Multisite action (fungicide)	Cu ↑, Mn ↑, Zn ↓	Inhibits fungal activity	Cu ↑ 13.2%, Mn ↑ 3.38%, Zn ↓ 12.9%	Complexation with Zn reduces availability; low microbial recovery	Paul *et al.* (2013)
22	Carbofuran + CTAB	Cationic + Surfactant	Cholinesterase inhibition + surfactant effect	Cu, Zn adsorption ↑	High retention in soil colloids	Not quantified	Enhanced nutrient adsorption; risk of reduced translocation	Singh *et al.*, 2000
23	Mancozeb (≤250 ppm)	Fungicide	Multisite electron transport disruption	↓ Nitrification, ↓ Ammonification	↓ Actinomycetes & fungi; ↑ P solubilization	NO_3^- ↓ 40%, NH_4^+ ↓ 60%, P ↑ 30%	Low doses inhibit microbial turnover; P solubilization increases at ≥250 ppm	Walia *et al.* (2014)
24	Mancozeb (≥1000 ppm)	Fungicide	Persistent toxicity	↓ Microbial biomass C, ↓ CO_2 evolution	↓ Bacteria, fungi, nitrifiers, ammonifiers	Biomass C ↓ 80%, CO_2 ↓ 33%	High doses suppress microbial respiration and carbon cycling	Walia *et al.* (2014)
25	Mancozeb (≥10 ppm)	Fungicide	Enzyme inhibition	↓ Organic matter turnover	↓ Amylase, Invertase, Phosphatase activities	Amylase ↓ 40%, Invertase ↓ 50%, Phosphatase ↓ 60%	Enzyme suppression persists beyond 4 weeks of incubation	Walia *et al.* (2014)
26	Imidacloprid	Insecticide	Nicotinic acetylcholine receptor agonist	Nitrogen (N) (nitrification affected), Carbon (C) cycling (altered)	Altered microbial community structure; impact on enzyme activities involved in N and C cycling	N (nitrate) ↓10-25% (due to altered nitrification rates)	While generally considered less disruptive than some older pesticides, it can still influence specific microbial groups involved in nutrient cycling.	Cycon *et al.* (2012)

on agricultural & horticultural crops, on 2.2 million ha. Glyphosate has been considered an environmentally safe herbicide because it is assumed to be inactivated quickly after spraying due to rapid sorption onto particles in the soil, and its fast degradation by microbes. The major toxic action of glyphosate results from inhibition of the enzyme 5-enolpyruvyl shikimate-3-phosphate synthase (EPSP synthase). This enzyme is critical in the shikimate pathway and its inhibition results in reduced biosynthesis of aromatic amino acids that subsequently impairs general metabolic processes such as protein synthesis. In Sunflower and Velvetleaf plants, cationic nutrients such as Mn, Fe, and Cu bind to the glyphosate molecule via its carboxyl and phosphonate groups to form stable complexes with glyphosate. Such complexes severely reduced the absorption and translocation of glyphosate within the treated tissue and thus limited its efficacy in weed control.

Glyphosate is antagonistic to the uptake, transport, and accumulation of Fe and Mn in sunflower plants. The study shows that sub-herbicidal rates of glyphosate effectively reduce the uptake and transport of Fe and Mn in plants. In agricultural systems with intensive glyphosate application, contamination of crop plants with glyphosate commonly occurs because of glyphosate spray drift and root uptake of glyphosate residues from soils

Zn^{2+}, Cu^{2+} and MnO_2

The results reveal that as compared to control, 2,4-D increases the available Cu (21.7%) and Zn (119.4%) during later stages and Mn (8.7%) almost increase throughout the incubation period. Endosulfan, contrarily caused immobilization of Zn (42.1%) during later stages, Cu (10.3%) in the intermediary stage and Mn (64.7%) throughout. Dithane M-45, caused immobilization of Zn (12.9%) during intermediary stage and Mn in early (3.0%) and late stages (6.7%) of incubation (Paul *et al.* (2013)

Reduce the Impact of Pesticides on Soil Health

IPM is a sustainable method that combines chemical, mechanical, and biological control techniques to reduce the use of pesticides. Important procedures include promoting the use of nematodes and ladybirds as natural predators to manage pests. Intercropping and crop rotation can be used to break the life cycles of pests. Keep an eye on pest populations and use pesticides only when required. The health of soil is less affected by organic and bio-based pesticides that come from natural sources like beneficial bacteria and neem oil. Among the benefits are reduced toxicity to non-target organisms and helpful microorganisms. Quicker decomposition in the soil lowers the buildup of residue over time. Improved nutrient cycling and soil biodiversity. High organic content and healthy soil are more resilient to pesticide damage. Applying manure and compost will increase microbial activity and improve organic matter. Enhancing soil structure with green manure and cover crops. Minimising tillage to maintain the integrity of the soil. The detrimental effects of pesticides can be considerably reduced by lowering their use and frequency. Think about using the appropriate dosage and timing of pesticide applications. Applying specific application methods, like drip irrigation and spot treatments. Selecting pesticides that are less persistent in the environment (Prashar and Shah, 2016).

Conclusion

In case of triazole fungicide like propiconazole at recommended dose enhanced the growth and activity of soil microbes and enzymes in an incubation study. However, at higher dose of its application became detrimental to the soil health (Ferrigo *et al.* (2018). The broad utilization of glyphosate and the ecological dangers related with it warrant mindfulness among its clients about its sensible use and require further exceptional examinations to relieve, dodge, or expel the issues coming about because of its utilization (Sharma *et al.* (2001). Lu *et al.*, (2020) reported that additions of chlorpyrifos (1 and 8 mg kg^{-1}) to soil resulted in significant decrease in the nitrogen fixation by reducing nitrogenase activity. Soil fertility is crucial for maintaining sustainable agricultural production for food and nutritional security in the world. Pesticides are essential inputs for enhancing agriculture production through the elimination of soil borne insects-pests and pathogens.The results, it can be concluded that pesticides impart differential influence on to be had cationic micro-vitamins in addition to feasible microorganism and fungi in soil. Among the pesticides, the insecticide, endosulfan creates detrimental environment on soil atmosphere and so want utmost precaution even as application. On the contrary, herbicide, in general, imparts beneficial influence on the cationic micronutrients as well as microbial communityHowever fungicide greater or less induced both useful as well as harmful effect on to be had micro-vitamins and negative effect on fungi. Among the pesticides, 2, 4-D generates the excellent soil environmentHerbicide had a temporary impact on soil health as well as soil microbial biomass parameter. Effect of different pesticide on properties of soil, i.e., electical conductivity, and organic carbon, became negligible. It suggests that the applications of pesticide like glyphosate or others limit the microbial growth initially, and no sustained ill effect on the growth of microbes up to the harvest of the crops.

Conflict of Interest

The authors declare that they have no conflict of interest.

Fig.10: Effect of glyphosate on growth of 20-day old sunflower plants (upper picture) and leaf chlorosis in young leaves (lower picture)

1. Adopt Integrated Pest Management (IPM)

- IPM is a sustainable approach that minimizes pesticide use by combining biological, mechanical, and chemical control methods.
- Key practices include: Encouraging natural predators (e.g., ladybugs, nematodes) to control pests.
- Using crop rotation and intercropping to disrupt pest life cycles.
- Monitoring pest populations to apply pesticides only when necessary.

2. Use Organic and Biopesticides

- Organic and bio-based pesticides derived from natural sources, such as neem oil and beneficial bacteria, are less harmful to soil health. Advantages include:
- Lower toxicity to beneficial microbes and non-target organisms.
- Faster breakdown in soil, reducing long-term residue accumulation.
- Enhanced soil biodiversity and nutrient cycling.

3. Improve Soil Organic Matter

- Healthy soil with high organic content can better resist pesticide damage. Enhance organic matter by:
- Applying compost and manure to boost microbial activity.
- Using cover crops and green manure to improve soil structure.
- Practicing minimal tillage to preserve soil integrity.

4. Optimize Pesticide Application

- Reducing the amount and frequency of pesticide use can significantly lessen its negative impact. Consider:
- Applying pesticides at the right time and in the correct dosage.
- Using targeted application techniques, such as spot treatments and drip irrigation.
- Choosing pesticides with lower environmental persistence.

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