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REVIEW ARTICLE

Soil-pesticide interactions: a review of residual behaviour and environmental impact

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Abstract

Agrochemicals had enabled more than double the food production over the past century and the continued need to feed a growing global population remained the basis for the widespread application of pesticides and fertilisers. Asia alone consumed over half of all pesticides manufactured worldwide. Population growth over the 20th century was highly correlated with increased food production, many of which had relied upon pesticide use. Agriculture provided 70 % of employment in India and hence formed the prime sector of the country's economy with around one-third of agricultural output being dependent on the use of pesticides. Crop production would drastically have come down without the use of pesticides. The critical question was that liberal use of pesticides posed acute environmental and public health risks, where improper and unregulated application left soil, water and food systems contaminated. With increasing food production, there was an urgent need to minimize toxic contaminants and enhance food quality. Bio-pesticides had emerged as a promising alternative to chemical pesticides in supporting sustainable agricultural development while reducing pollution. Another growing development in India was in bio-pesticides, an effective alternative to chemical options. Organic residues for the improvement of soil health could have been another cost-effective and sustainable means of reducing pesticide pollution. However, all such measures were pointless in the absence of a clear understanding of the interplay between pesticides and soil properties further governing their fate and transport in the ecosystem.

Keywords: agriculture; environment; genetic engineering; organic fertilizers; pesticide

Introduction

Pesticide like herbicides, insecticides, fungicides, rodenticides and nematicides whether natural or synthetic, were used to control pests, weeds and diseases in various agricultural practices and Since World War II, synthetic pesticide use had rapidly increased to control pests, reduce crop losses and improve yields and food quality (1). Crop losses due to insect pests remained high in both developing and developed countries and minimizing these losses and improving pest management for diseases and weeds required significant effort. With the advent of agricultural development that involved the enhancement of crop production and protection, pesticides became vital components for use to improve crop production and agriculture in general to boost agricultural productivity worldwide and Pesticides were generally categorized based on a variety of classifications and were grouped mainly on the types of pests they were designed to destroy including herbicides, insecticides, fungicides, rodenticides and nematicides. While pesticides offered better quality and quantity of food and led to reduction in insect-borne diseases, they also posed to potential environmental damage with particular implications for water systems. The major concern that arose from persistent and intensive pesticide use resulted in serious effects on biodiversity (2, 3). According to previous studies the global population was projected to grow to approximately 8.5 billion by 2030, 9.7 billion by 2050 and 10.9 billion by 2100 and population growth, especially in developing countries, was expected to increase the demand for food production (4). This demand was driven by shifting dietary preferences toward higher-quality foods, including greater consumption of meat and dairy, along with increased use of grains for livestock feed (5). Unfortunately, more than half of these pesticides sprayed on crops ended up in environment causing harmful ecological damage. Pesticides tended to spread in rivers and lakes due to runoff from agricultural fields nearby and industrial discharges. Although soil acted as a reservoir for agrochemicals due to their affinity to soil particles, the intimate relation between soil and water bodies created a risk of contamination in surface water sources-such as streams, estuaries and lakes-as well as groundwater. Even small pesticide concentrations in water had the potential to accumulate through the food chain, affecting aquatic species and, through consumption, ultimately impacting human health (6, 7).

Pesticide contamination negatively affected soil quality, changing its chemical and biological properties, which in turn affected crop yields. The most widely used pesticides included organochlorines such as DDT, Lindane and Endosulfan; organophosphates like Malathion, Dichlorvos and Diazinon; carbamates such as Carbaryl, Carbofuran and Aminocarb; and pyrethroids such as Permethrin, Cypermethrin and Fenvalerate. Poor management of pesticides had resulted in increased pollution of surface and groundwater over the past years. Precipitation levels, as well as irrigation, had increased overland flow and more pesticide leaching into the soil (8, 9). This review explored new strategies for pesticide removal, focusing on their impact on living systems, bioremediation methods and complete residue elimination.

Mode of action of pesticides

Pesticides were widely used to enhance agricultural output and food preservation, often ignoring their risks. To address issues like overuse and exposure, careful application and diverse pesticide categories were essential. The extensive use of pesticides had led to negative impacts, emphasizing the need for effective waste management (Fig. 1). Pesticide biodegradation offered an environmentally friendly solution for long-term pollution control, with microorganisms playing a crucial role in breaking down pesticides. Recent studies had shown that microbes from sewage and soil could effectively degrade these chemicals. However, information on pesticide classifications (Fig. 2), toxicity and remediation remained limited (10-12). Most pesticides were applied to agricultural land. Herbicides killed weeds, insecticides targeted insects in different settings and fungicides prevented fungal infections in plants or seeds. Pesticide toxicity was largely determined by the dose and exposure time, affecting both acute and chronic effects. Acute toxicity referred to short-term harmful

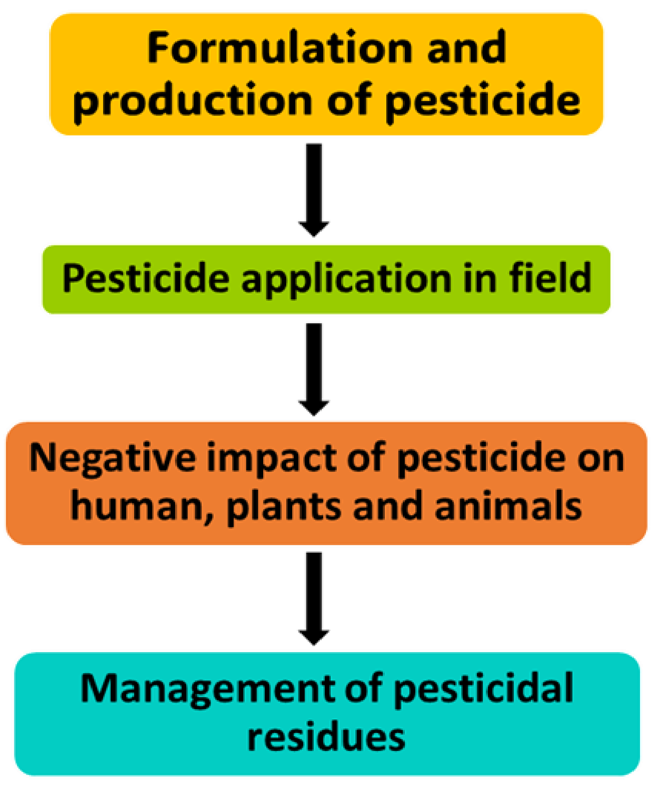

Fig. 1. Flow chart: Need for pesticidal residue management.

effects on animal, plants and humans, with highly toxic pesticides being lethal even in small amounts. Pesticides could also be divided based on their action, in which they either killed pests, reduced the number or severity of pest infestation, or repelled it. Fig. 3 illustrated structures on commonly employed pesticides such as organochlorines, organophosphates, carbamates and pyrethroids (9, 11). The WHO classified pesticides based on acute toxicity using the LD_{50} and the category was divided into acute dermal and acute oral toxicities (Table 1) (13).Pesticides targeted specific sites or processes in pests, disrupting their physiology to make them harmless. This interaction, involving enzymes, receptors, or membranes, could harm or kill the pest. Insecticides and herbicides typically focused on 4 to 6 targets, making up 75 % of global sales. Insecticides acted quickly, affecting neurotransmission to prevent damage, while herbicides disrupted plant-specific pathways, killing weeds over time. Fungicides targeted essential functions in fungi, often acting as fungi stats, allowing the plant's immune system to finish off the disease. The primary interaction typically occurred with the pesticide at picomolar or nanomolar levels, with secondary interactions at higher concentrations (14). Green plant pigments absorbed light and converted it into ATP in chloroplasts.

Table 1. Pesticides classification according to WHO guidelines (13)

Class	LD_{50} of rat		Hazardous level
	Dermal	Oral	
Ia	< 50 mg/kg body weight	< 5 mg/kg body weight	Extremely hazardous
Ib	50 to 200 mg/kg body weight	5 to 50 mg/kg body weight	Highly hazardous
II	200 to 2000 mg/kg body weight	50 to 2000 mg/kg body weight	Moderately hazardous
III	> 2000	> 2000	Slightly hazardous
U	>/= 5000	>/= 5000	Unlikely to present acute hazard

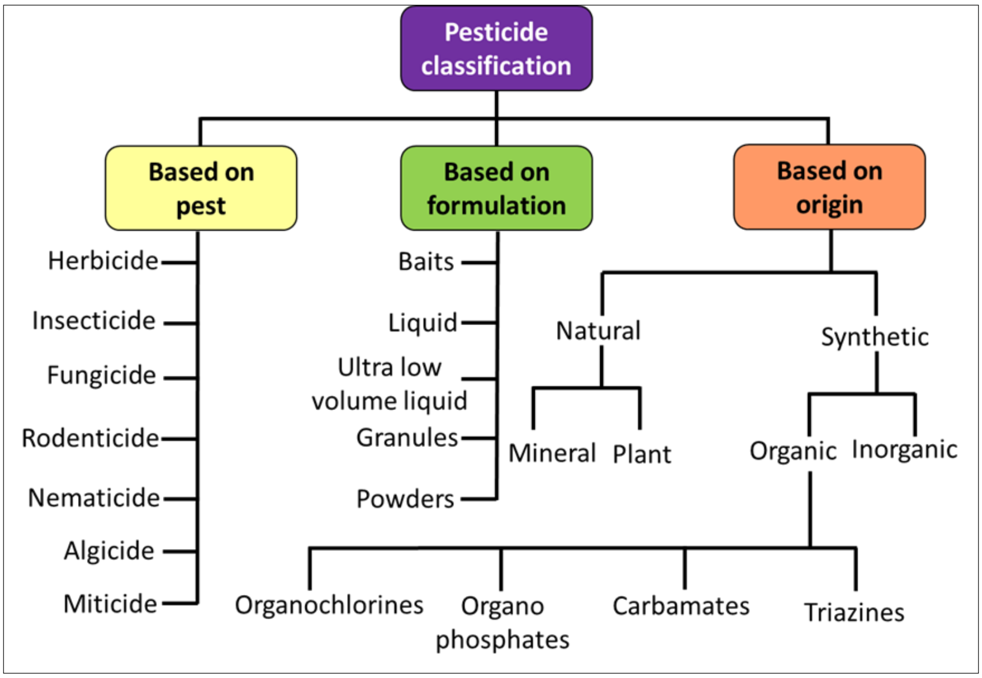

Fig. 2. Classification of pesticides (12).

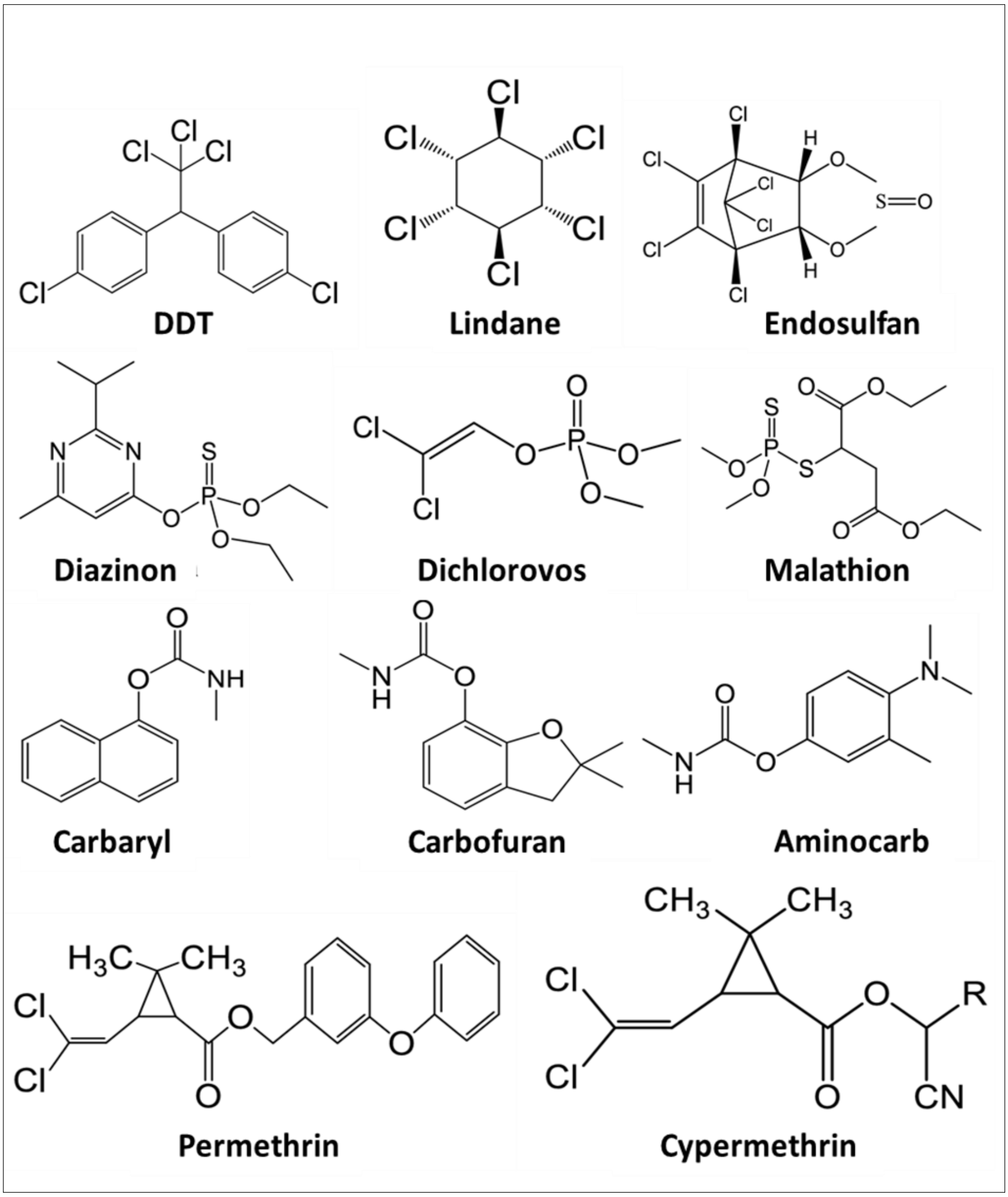

Fig. 3. Chemical structures of some commonly used pesticides (9, 11).

Herbicides targeting plant-specific processes had low toxicity to mammals and PSII, an early herbicide target, remained crucial with over 50 compounds affecting it. Resistance to one PSII inhibitor didn't affect others due to different target sites. Herbicides like paraquat (Fig. 4) disrupted PSI, while 26 targeted protoporphyrinogen IX oxidase, causing cell damage. Carotenoids protected chlorophyll from light damage and their absence led to bleaching. Phytoene desaturase and lycopene cyclase are sensitive to specific herbicides and other herbicides caused bleaching via different pathways (14, 15).

Plants synthesized their own amino acids, while animals needed them from their diet, making amino acid biosynthesis a prime target for herbicides, which didn't affect mammals. Key targets included EPSP synthase (glyphosate), AHAS/ALS (sulfonylureas and imidazolinones) and glutamine synthase (glufosinate) (Fig. 5). Resistance often arose from overexpressing these enzymes. Other herbicides also targeted microtubule systems, cell division and fatty acid synthesis, including ACCase inhibitors, while some inhibited cell wall biosynthesis, like dichlobenil (14, 16). Pesticide exposure often suppressed cholinesterase enzymes, such as acetylcholinesterase (AChE) and caused oxidative stress that led to many health problems. It interfered with the way organisms-maintained energy, resulting in the loss of stored energy and changed physiological activities. The effect depended on the type of pesticide, concentration, species, preventive measures, adsorption in the soil, weather and persistence, which made the risk assessment difficult for both organisms and the environment. Organophosphates and carbamates were widely used pesticides that inhibited cholinesterase and affected multiple organ systems, including nervous and respiratory systems (1, 17). AChE, which degraded acetylcholine, interacted more with muscarinic receptors than nicotinic ones. Inhibition of AChE caused acetylcholine accumulation, leading to overstimulation of the brain, especially at muscarinic sites (12).

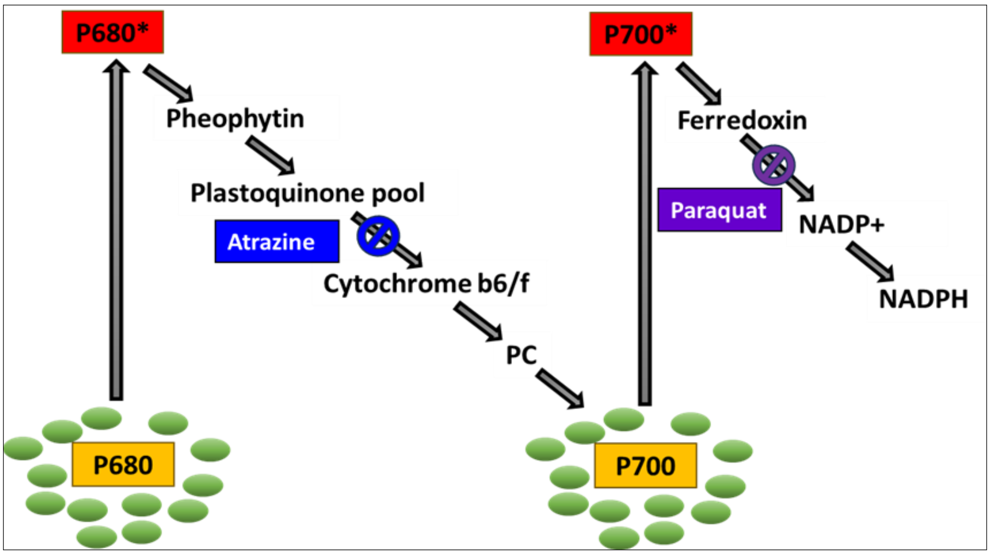

Fig. 4. Inhibition by Atrazine and Paraquat (14).

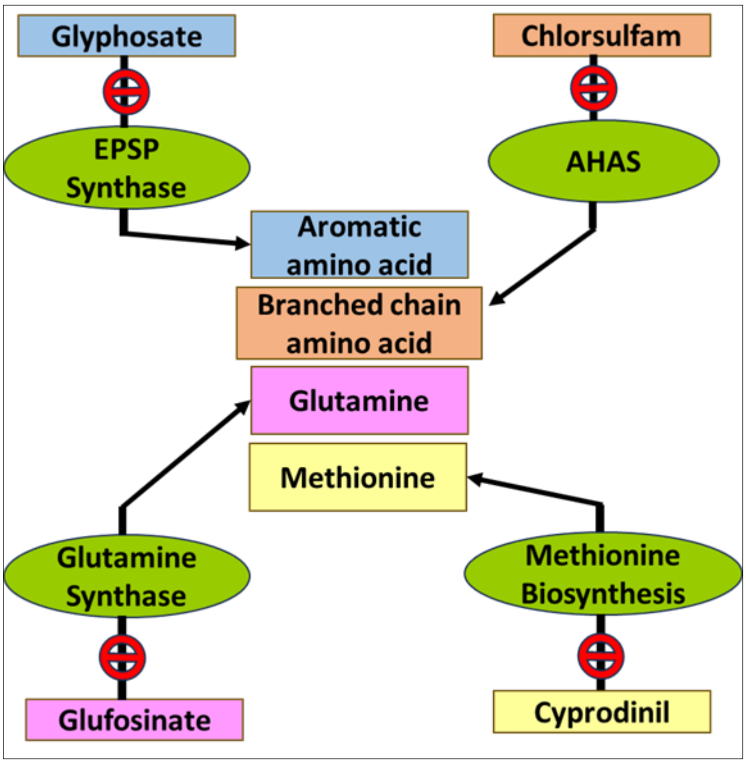

Fig. 5. Herbicides like glyphosate inhibiting amino acid synthesis (14).

Factors affecting application and absorption of pesticide in soil

Adsorption and desorption were factors that controlled the availability of pesticides in soil. They were influenced by factors such as clay content, organic matter, pH and salinity. Adsorption was the process in which pesticide particles interacted with the soil surface through physical or chemical bonds. It influenced pesticide degradation and movement. Though adsorption retarded microbial degradation, it might have facilitated non-biological degradation. Desorption determined whether soil was a permanent or temporary reservoir for pesticides, depending on the soil composition and the strength of the bond (18, 19). The water solubility of nonionic pesticides, like Diuron, did indicate an adsorption potential because its interaction with water represented the dominant process in a soil setting. Low soluble compounds showed poor adsorption and also higher biodegradation levels. However, no generalisations could be made between adsorption mechanisms (Fig. 6) (9, 20). Ionizability, based on functional groups, improved adsorption and the ionization of pesticides depended on the pH of the soil. Acidic pesticides were anionic at higher pH and basic ones were cationic at lower pH, both of which improved adsorptions. Nonionic pesticides might have become temporarily polarized, while hydrophilicity and lipophilicity also affected binding in soil (21-23).

Soil organic matter, though a small fraction of total soil mass, was vital for pesticide adsorption due to its chemical interactions with pesticides. Its complex structure, particularly humic substances, contained reactive groups like hydroxyls and carboxyl's that enhanced this process (22, 24, 25). Clay minerals also aided in pesticide retention, with their large surface area and hydrophilic nature reducing pesticide mobility and leaching (26). Soil microorganisms played a major role in pesticide degradation through enzymatic reactions that changed the pesticide properties. Bacteria, actinomycetes and fungi were the primary agents, though adsorption within the soil could have slowed down the degradation process over time (22, 27). Climate change impacted soil properties and pesticide application by decreasing the soil organic matter, increasing the erosion rate and increasing the movement of water and chemicals. Climate change affected crop distribution, pests and diseases, which indirectly impacted pesticide application. Changes in temperature, rainfall and CO_2 could have altered crop growth and yields, requiring changes in the type and quantity of pesticides and erratic rainfall and drought might have further reduced crop performance (28).

Climate factors like temperature, humidity, precipitation, radiation and dew substantially affected the type and distribution of crop diseases because these factors affected the plant host, pathogen and vectors to enhance disease severity and crop losses. High rainfall and high temperatures increased infectious diseases as well as spore germination. Milder winters enhanced the survival of pest and disease. Fluctuations in humidity and temperature also influenced fungal growth as well as disease incidence. Transformation, degradation, which consisted of photolysis and microbial breakdown and movement, which included volatilization, runoff and leaching, comprised pesticide behaviour in the environment and had been affected by climate change, as well as by climate variability. The primary contribution to pesticide pollution in the atmosphere was volatilization, driven by heightened temperatures, increased soil moisture and direct sunlight; it accelerated in the humid soil after rainfall (29).

The transfer of pesticides to the soil through leaching and into surface water through drainage mainly depended on the interaction of climate-soil-pesticide, which determined precipitation in volume, duration, seasonality, intensity and time. Temperature affected leaching primarily by modifying soil mineralogy and geochemistry. A negative correlation between temperature and leaching usually appeared during the desorption process in studies. Temperature also affected the seasonal transport of pesticides and decreased the impact of winter rainfall on the retention and degradation of residues from spring or autumn applications (28, 30). Moreover, global warming reduced the life cycle of vectors such as mosquitoes and increased disease transmission rates. Responses to climate varied between diseases; for example, pathogenic *Escherichia coli* showed a very strong correlation with temperature and humidity, whereas norovirus showed a negative correlation. Global warming increased microbial and chemical reaction rates that might have led to a reduction in pesticide concentrations in the environment through enhanced degradation of chemical components. Higher soil moisture as well as precipitation further enhanced pesticide degradation and persistence. Elevated humidity expedited degradation but complicated the initial process (28).

Pesticide contamination and its adverse effects on the natural environment and human health

There had been numerous cases of pesticide-related poisoning among farmers, rural workers and their families; even the spread of pesticide residues had caused mass die-offs of wildlife, which included bees, birds, fish and small mammals (31-33). These events prompted stricter pesticide regulation and massive

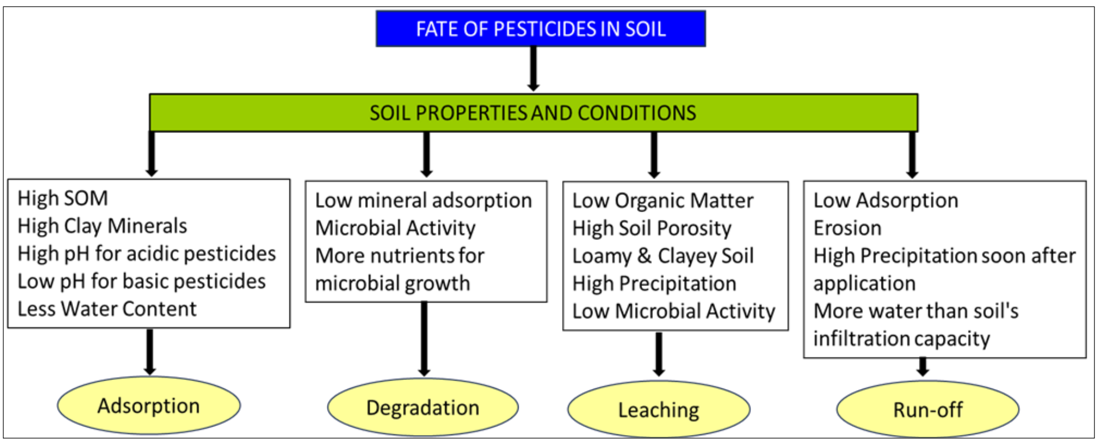

Fig. 6. Fate of pesticides in soil based on soil properties (9).

research into the environmental implications of these compounds, including persistence, toxicity and global contamination. Around the world, substances such as hexachlorocyclohexanes, chlordane and toxaphene, used in the southern United States, evaporated and were carried by the air, then condensed in cooler regions and fell on the Great Lakes and the most volatile compounds travelled faster and farther. The persistent chemicals DDT, HCH, toxaphene, aldrin and dieldrin were banned under the 2002 Stockholm Convention and were replaced with safer alternatives.

Organochlorines remained in soils, sediments and the environment, still posing risks. For example, toxaphene, though no longer used in Nicaragua, continued to contaminate aquatic ecosystems through runoff, threatening shrimp farming (8, 34). The fate and behaviour of pesticides were affected by processes such as adsorption-desorption, degradation, leaching and runoff, which determined the movement of pesticides from soil to surface water or groundwater. The key factors were how pesticides bound to soil organic matter or degraded through microbial or chemical action. The effects of these processes varied with the specific pesticide and soil characteristics, since pesticides differed in properties like hydrophobicity, ionic nature and acidity. In addition, soil structure and composition greatly influenced pesticide activity, resulting in large variability across different soil environments (9). Leaching was the process through which pesticides were transported down in the groundwater, driven by mass transfer and molecular diffusion. The pollution of groundwaters occurred due to pesticides leaching through soil layers, depending on soil quality, pesticide properties, type of formulation, irrigation practices and hydrogeological characteristics. More losses through other processes lowered the leaching potential. Thus, soil density and porosity, which dictated flow and retention of water, indirectly impacted pesticide transport from the surface to deeper layers of soil through macropore flow (35, 36). Soils that contained low organic matter and loam and clay content tended to have increased leaching risk when there was heavy rainfall, but dry conditions significantly reduced leaching. In addition, pesticide loss through leaching depended on the solubility and formulation; for instance, under similar conditions, propyzamide and benfluralin exhibited different leaching behaviours due to their solubility differences (37, 38).

There were correlations of pesticide properties in regard to water solubility, sorption constant, (Koc), octanol/water partition coefficient (Kow) and half-life (DT50) and persistence of residues of pesticides in soil. Generally, high Kow and Koc values were associated with pesticide which was strongly bound with the soil and leads to extensive accumulation, especially the hydrophobic and bio accumulative type. For example, strongly binding organochlorine pesticides such as DDT and endosulfan led to bans in several countries, including China. However, less persistent pesticides like carbamates and fungicides could still leach and run off into the environment. Thus, the pesticide contamination in soil posed severe threats to the food chain and water sources (29). Besides this in 2015, over 20000 Indians died from pesticide self-poisoning. While suicides had steadily increased since 1981, little change occurred in suicide or pesticide suicide rates since 2001. In contrast, Sri Lanka and Bangladesh saw significant declines in both after enforcing pesticide regulations. India's 2011 endosulfan ban led to a small decrease in overall suicides and a larger drop in pesticide-related suicides, similar to Sri Lanka's decline after banning Class I pesticides (39). Updated list of pesticides banned for manufacture, import and use was displayed in Table 2 (40).

Over the years, synthetic pesticides such as herbicides, insecticides and fungicides were applied to increase crop yields. But through overuse and runoff during rainfalls, they contaminated water bodies, which might have harmed aquatic life and increased the harmful chemicals in fish, leading to diseases like cancer, diabetes and liver damage. Synthetic pesticides also harmed the soil, plants and animals. This shifted toward organic biopesticides (Table 3) that were cheaper, eco-friendly and sustainable. Biopesticides included microbial pesticides, plant-derived substances and nanoparticles. These alternatives were

Table 2. List of banned pesticides of India (manufacture, import and use) (40)

1	Carbaryl (S.O 3951(E) dated 8th August, 2018)	26	Toxaphene (Camphechlor) (S.O. 569 (E) dated 25th July 1989)
2	Pentachloro Nitrobenzene (PCNB) (S.O. 569 (E) dated 25th July 1989)	27	Phenyl Mercury Acetate
3	Linuron (S.O 3951(E) dated 8th August, 2018)	28	Trichloro acetic acid (TCA) (S.O. 682 (E) dated 17th July 2001)
4	Menazon	29	Tridemorph (S.O 3951(E) dated 8th August, 2018)
5	Dibromochloropropane (DBCP) (S.O. 569 (E) dated 25th July 1989)	30	Fenarimol (S.O 3951(E) dated 8th August, 2018)
6	Sodium Cyanide (banned for Insecticidal purpose only S.O 3951(E) dated 8th August, 2018)*	31	Fenthion (S.O 3951(E) dated 8th August, 2018)
7	Calcium Cyanide	32	Chlordane
8	Chlorbenzilate (S.O. 682 (E) dated 17th July 2001)	33	Triazophos (S.O. 3951 (E), dated 08.08.2018)
9	Methomyl (S.O. 4294(E) dated 3rd October, 2023)	34	Ethylene Dibromide (EDB) (S.O. 682 (E) dated 17th July 2001)
10	Paraquat Dimethyl Sulphate	35	Chlorofenvinphos
11	Phosphamidon (S.O. 3951 (E), dated 08.08.2018)	36	Ethyl Parathion
12	Dichlorovos (S.O. 3951 (E), dated 08.08.2018)	37	Metoxuron
13	Phorate (S.O. 3951 (E), dated 08.08.2018)	38	Dinocap (S.O(S.O. 4294 (E) dated 3rd October, 2023)
14	Dieldrin (S.O. 682 (E) dated 17th July 2001)	39	Sodium Methane Arsonate
15	Endosulfron (ad-Interim order of the Supreme Court of India in the Writ Petition (Civil) No. 213 of 2011 dated 13th May, 2011 and finally disposed of dated 10th January, 2017)	40	Diazinon (S.O 3951(E) dated 8th August, 2018)
16	Thiometon (S.O 3951 (E) dated 8th August, 2018)	41	Nitrofen
17	Methyl Parathion (S.O 3951 (E) dated 8th August, 2018)	42	Endrin
18	Alachlor (S.O. 3951 (E), dated 08.08.2018)	43	Heptachlor
19	Lindane (Gamma-HCH)	44	Copper Acetoarsenite
20	Maleic Hydrazide (S.O. 682 (E) dated 17th July 2001)	45	Dicofol (S.O. 4294(E) dated 3rd October, 2023)
21	Aldicarb (S.O. 682 (E) dated 17th July 2001)	46	Trichlorfon (S.O. 3951 (E), dated 08.08.2018)
22	Benzene Hexachloride	47	Pentachlorophenol
23	Benomyl (S.O 3951(E) dated 8th August, 2018)	48	Ethyl Mercury Chloride
24	Aldrin	49	Tetradifon
25	Methoxy Ethyl Mercury Chloride (S.O 3951(E) dated 8th August, 2018)		

Table 3. The all India statistics included in data on the total area under cultivation and the extent of of chemical & bio- pesticides use (49)

S. No.	Year	AREA UNDER (Unit: '000' Hectare)					
		Cultivation	Pesticides				Not under use of pesticides
			Chemical	Bio	Both chemical and bio	Total	
1	**2018-19**	141555	81120	7119	10572	98812	45628
2	**2019-20**	198552	108035	14636	37874	160545	52874
3	**2020-21**	188595	111289	14014	22046	147349	59942
4	**2021-22**	195875	96042	16868	14075	126985	68891
5	**2022-23**	207562	108216	15636	21273	145126	62436

more targeted, have fewer health risks and were biodegradable. Biopesticides were effective in pest management due to their multiple modes of action, including disrupting gut function, growth and metabolism, as well as denaturing proteins, causing paralysis and releasing toxins (41). These actions helped overcome pest resistance more effectively than chemical pesticides. Studies showed that biopesticides were eco-friendly, biodegradable, low in toxicity and target-specific, with minimal impact on non-target organisms. The adoption and use of biopesticides in agriculture faced several challenges despite its advantages. They were often considered less effective and slower in pest control, were expensive and were not widely available. Additionally, biopesticides suffered from quality control issues, short shelf life and concerns about dosage and pest resistance. While biopesticides offered benefits, their efficacy depended on the source and composition, with some acting by disrupting protein translation or plasma membrane permeability in pathogens (42-45).

Biopesticides had been found to be an effective and cost-efficient solution for the management of insect pests and weeds in agriculture and public health in India since over 50 years. Biopesticides positively contributed to improving agricultural productivity and farmers' global income. Currently, India was self -sufficient in the production of biopesticides and exported them as well. One of the most frequently used species in the Indian biopesticide industry was *Trichoderma viride* (46). Biopesticides, by 2023, grew at an average annual rate of 8.64 % and made up more than 7 % (USD 4.5 billion) of the global crop protection market. Biopesticides were also expected to be comparable to synthetic pesticides in market size by the late 2040s or early 2050s. However, there existed huge uncertainties regarding their adoption rates, especially in regions such as Africa and Southeast Asia, which made the variability in these projections (47, 48).

Biotechnological and biochemical degradation of pesticides from the environment

Microorganisms, including bacteria and fungi, were efficient in pesticide bioremediation, although the efficiency of single strains was usually low. Therefore, there has been a focus on microbial consortia, which have greater potential for breaking down pesticides. The rate of degradation depends on the chemical properties of the pesticide and available metabolic pathways, with some pesticides like atrazine degrading faster than others like pentachlorophenol (PCP), polychlorinated biphenyls (PCBs). While axenic cultures have been handy in studying metabolism, mixed microbial cultures were more effective because they distribute tasks between species to handle complex compounds in the same way microbes' work in nature (50, 51). Microbial consortia were present everywhere in nature and can efficiently degrade pesticides through various metabolic pathways. Unlike monocultures, they perform complex functions and were more resilient to environmental changes. Quorum sensing helps to distribute degradation tasks within the consortium, which can further be involved in neutralism, commensalism, amensalism, competition, predation and cooperation. Consortia may include various species that collectively help to achieve complex functions such as syntrophic pesticide degradation. It thus involves signalling molecules, specifically acyl-homoserine lactones (AHL) in Gram-negative bacteria and peptides in Gram-positive bacteria. The principal challenges in engineering stable microbial consortia were the problems of maintaining efficient metabolic interaction and preventing cheating strains (52-54).

Computational tools were used to model microbial behaviour and design new metabolic interactions for large-scale pesticide degradation. The molecular tools, including CRISPR-Cas9, had advanced gene editing for bioremediation. While consortia presented benefits like faster metabolism and environmental stability, challenges still existed in their development, including strain interactions, stability in soil and preservation. Despite the challenges, microbial consortia held much promise for pesticide degradation (51, 55). Pesticide biodegradation mainly occurred through microbial systems that produced specific enzymes to break down pesticides in contaminated environments. Pure and mixed cultures of bacteria and fungi, especially microbial consortia, effectively removed pesticide residues from soil and water (51). The key bacterial genus involved were *Streptomyces, Burkholderia* and *Pseudomonas*, while other types of phyla such as *Actinomycetota* and *Proteobacteria* had a strong degradative ability. Recent advances in microbial cellular immobilization (CI) enhanced the longevity and reusability of microbes for degradation. Factors such as microbial culture, cultivation techniques and environmental conditions influenced degradation efficiency (56). Compared to pure cultures, microbial consortia improved breakdown in bio-purification systems while Biobed systems fostered specialized microorganisms for pesticide degradation in wastewater. However, the effectiveness of bioaugmentation in high concentration wastewater was still under researched (11). The ability of microbes to metabolically remediate pollutants was related to their genetic makeup. Biotechnological methods helped extract genes from contaminated areas for study; however, they often were applied for one gene or enzyme, which is limiting large-scale study. Sequencing techniques including 16S rRNA for bacteria and internal transcribed spacer regions for fungi helped identify and analyze the phylogenetics of microbial communities and metagenomics allowed community analysis. It was demonstrated that specific genes, such as the organophosphate-degrading *opd* gene, were upregulated in response to pesticides and microbial community structures changed during degradation. Heterologous gene expression was effective for isolating pesticide-degrading genes, with advances in genetic engineering facilitating detection (51, 57-59). Understanding gene expression in bioremediation was crucial, as there was often a correlation between bioremediation genes and contaminants and mRNA levels could indicated degradation rates (60). This method combined mRNA quantification with 16S rRNA analysis to identify effective microbial strains. However, factors such as nutrient levels and pH could limit microbial growth during degradation. Evaluating metabolites linked to contaminated sites enhanced bioremediation efforts. Genomics-based studies had evolved to include microbial consortia, marking a new era for understanding pesticide-degrading microbes. Numerous complete genomic sequences were now available, supporting the development of effective degradation strategies through whole-genome analysis (61, 62).

The chemical and physical methods of cleaning pesticide residues often released more toxic compounds, thus making harmful and eco-friendly bioremediation methods like phytoremediation, microalgae bioremediation, myco-remediation, which used plants, algae, fungi and bacteria a low-cost and safe approach for contaminant removal. Phytoremediation was an inexpensive, solar-powered process that employed specific plants to remove or reduce harmful chemicals from contaminated sites. For instance, notable species included *Kochia sp*., *Triticum spp*., *Ricinus communis* and *Ceratophyllum demersum*, which could completely degrade atrazine, lindane, chlorpyrifos and endrin. These plants broke down the dangerous substances into less harmful types via phytovolatilization, rhizo-degradation, phytodegradation and phytoextraction mechanisms. Also, landscapes were beautified and erosion decreased through preventing pollutants leakage and the pollutants leaking into the soil, so safe and environmental-friendly waste disposal. Microalgae were very good biosorbents for heavy metals and pesticides and they could remove these contaminants from contaminated areas. They removed substances such as atrazine very effectively. These organisms converted light energy into chemical energy with the production of oxygen that supported environmental balance and bacterial biodegradation. Microalgae performed several functions, such as nutrient recovery from wastewater, biomass production and contaminant removal by bioaccumulation and biosorption. Bioaccumulation was an active process where it involved living organisms, while biosorption was energy-independent and included both living and dead cells. This technology enabled the accumulation of pesticides and transformed toxic compounds into less harmful forms. The major factors affecting pesticide degradation were the type of microalgae, environmental conditions and pesticide characteristics such as molecular weight and water solubility. Microalgae could consume both light and organic carbon during stress, hence their superiority over bacteria and fungi in the degradation process (11, 63, 64).

Contribution of organic residues in pesticide degradation and improving soil health

Modern agriculture largely utilized organic waste products like farmyard manure, crop residues and marine animal remains to improve crop growth, especially in Europe and the USA. Soil under intensive farming was susceptible to degradation and required high addition of fossil fuels for fertilizers, pesticides and irrigation. Yet, these measures enabled pollution of the environment, health hazards, loss of habitat, increased energy consumption and eventually unsustainable agriculture (65). The organic amendments improved soil properties, promoted soil health and reduced landfill waste. They provided essential nutrients for microbial activity and plant growth while improving soil structure, porosity and water retention. They modified the pesticide behaviour, which eventually favours adsorption as it discouraged groundwater contamination. Moreover, the most usual addition was biochar; it, further helped in soil contaminations control. The carbonous pyrolyzed substance derived from biomass had its major application in combating eco-contaminations. That was due to its excellent specific area and porosity, which helped in absorbing a wider concentration of pesticides in question while reducing their level toxicity in the environment. Biochar also supported mine tailing rehabilitation, reduced salt stress in plants and enhanced oil-polluted soil biodegradation.

Pesticide degradation was a function of environmental conditions and microbial action and organic matter content appeared to play a significant role. It had been found that organic amendments modified herbicide bioavailability and degradation in some cases and reduced dissipation by enhancing adsorption (9, 66). Soil health improvement contributes to food security also the FAO also launched the "Global Soil Partnership" to fight soil degradation and encourage healthy soils for international food security. There were four dimensions of food security such as food production and availability through soil management, food supply stability, food access through physical and economic means and food safety and nutritional quality (67, 68).

Conclusion

For many years, pesticides had served as a quick and affordable solution to control pests and weeds in Indian agriculture, boosting crop yields and farmer incomes. While India was self-sufficient in pesticide production, the country urgently needed proper regulation to curb large-scale environmental pollution. Biopesticides offered a sustainable and eco-friendly alternative, but their adoption required strong collaboration between public and private sectors to improve policy frameworks. The use of organic residues in farming helped reduce pesticide contamination in soil and groundwater. Future research was expected to focus on the development and understanding of microbial consortia, particularly their diversity and function in pest management. Databases containing information on nutrient needs, metabolic profiles and microbial interactions supported the design of effective microbial consortia. Synthetic microbial communities could have played a major role in large-scale pesticide degradation. Meanwhile, innovations like GMO crops had to be developed cautiously, with thorough risk assessments and international cooperation to ensure food safety and security based on scientific and ethical principles.

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Authors' contributions

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