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Research Article

INTERNATIONAL JOURNAL OF APPLIED BIOLOGY AND PHARMACEUTICAL TECHNOLOGY

ISSN: 0976-4550

Different Categorizations of Synthetic Pesticides and Their Effects on Soil

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Abstract

The present study illustrates the effect of all types of chemical pesticides on soil nature. It includes the classification of insecticides, herbicides, fungicides, bactericides and viricides. The study focuses on all types for each category explaining the degree of impact on soils in terms of soil persistence and accumulation, soil microbial impacts, soil enzyme inhibition, soil fertility, groundwater contamination and pesticide degradation. Diagrammatic schemes illustrate the pesticide mechanisms on soil structure. The study gives an overview on pesticide impact and discusses at conclusion section how to reduce harmful soil induction and show the suggested solutions.

Keywords: Organic matter, Leaching, dehydrogenase, Inhibition, *Rhizobium*

Introduction

Pesticides, insecticides and fungicides are the most common use in removal all types of pathogen presented externally and internally at crop plants to conserve them and increase output yield to improve life style of human beings after fulfill all their vital and main requirements. Unfortunately, they affect negatively on all basic abiotic global components like air, water and even soils (Adamski *et al*., 2009). Soil component includes physical, chemical and biological structures where they are destroyed within short or long-terms. Ecosystems can be influenced whether terrestrial or marine to give complete destruction on the planet. Precautions and thinking future plans should be direct to safe both agriculture and human life (Alford and Krupke, 2017). Different measurements can be accomplished to evaluate the state of soil health. Water management within soil profile after pesticide treatment will be calculated. The number of beneficial and non-beneficial microorganisms should be counted (Kronberg *et al*., 2018). Soil texture with chemical fluent are determined. Chemical components, minerals, chelation and mixtures are considered. Various procedures and analysis should be continuously executed to conserve soil sustainability (Tari *et al*., 2021). The aim of this study to give a complete picture of the effect of all types of insecticides, herbicides, fungicides, bactericides and viricides on soil nature in presence of soil persistence, soil microbes, soil fauna and risk of environment.

Main Chemical Types of insecticides

Organochlorines (OC)

They have significant influence on soil nature because they last at soil profile for long time due to their stability and lipophilicity besides they are regarded as the main bioaccumulator at food chains. DDT, Lindane, Dieldrin, Heptachlor and Aldrin are examples of them. Due to their toxicity,

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Citation: A. El-Shabasy, Hammad Ahmad Jan, Ahmed Ali Mustafa. Different Categorizations of Synthetic Pesticides and Their Effects on Soil. International Journal of Applied Biology and Pharmaceutical Technology. 16 (2025): 12-29.

Received: August 28, 2025
Accepted: September 03, 2025
Published: September 09, 2025

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DOI:10.26502/ijabpt.202136

some countries give some restrictions on dealing with them (Armitage and Gobas, 2007).

Persistence and Accumulation

They are fat soluble so they are able to stay from months to decades with soil particles binding to organic matter as well as clay particles. They are discovered at levels of food chains especially with successive treatments (Miglioranza *et al*., 2013).

Soil Microbial Impact

According to their toxicity, beneficial microbial communities are altered whether at nature, structure or diversity. They suppress all beneficial bacteria and mycorrhiza as well as dirupt the nutrient cycles occurred at soil profile as decomposition and nitrogen fixation (Mishra *et al*., 2012).

Soil Enzyme Inhibition

The vital microbial and phyto-enzymes are inhibited like urease, dehydrogenase and phosphatase so that organic matter and nutrient can't be processed (Kottler *et al*., 2001).

Bioaccumulation and Biomagnification

Utilization of polluted remains are still present at food web by soil-dwelling organisms as earthworms. They are transferred through heterotrophs by predators (Weber *et al*., 2010).

Reduced Soil Fertility

Plant productivity is reduced by degradation of mineral availability induced with long-term exposure as well as alteration of chemical properties of soil texture like soil PH (Rodriguez-Campos *et al*., 2014).

Groundwater Contamination

Ground water is affected and contaminated especially small soil profile with sandy or disturbed soil particles (Simı´dova and Hofman, 2014).

Organophosphates (OP)

Unfortunately, they are wide spread at soil with high harmful impact compared with previous one due to highly degradation with bad health effects. Parathion, Chlorpyrifos, Parathion, Dimethoate, Diazinon and Malathion are good examples. They are able to inhibit nerve stimulator like acetylcholinesterase. They are vey toxic on all types of organism even humans (Monkiedje, 2002).

Soil Microbial Impact

Obviously, they suppress the most beneficial bacteria that involved in nitrogen fixation like *Rhizobium* and *Azotobacter*. Moreover, They reduce and decline microbial resistance and diversity respectively. They inhibit the organic matter decomposition with bad effects on nutrient cycling (Liu *et al*., 2005).

Enzyme Activity

The most important enzymes are altered and become inactive like dehydrogenase, phosphatase and urease that influence on soil fertility and nutrient availability (Mihajlovic *et al*., 2011).

Residue and Degradation

They can be degraded by hydrolysis mechanism, photo-degradation and microbial activities. They stay at soil from days to a few weeks according to abiotic factors like moisture, PH and temperature. Some metabolites are extracted from Organophosphates metabolism where are more or less toxic via biodegradation (Muñoz-Quezada *et al*., 2016).

Soil Fauna

Different types of living organisms can be affected by toxicity of Organophosphates like nematodes, earthworms and other beneficial invertebrates at aeration and structure (Pandey *et al*., 2019).

Carbamates

Aldicarb, Carbaryl (Sevin), Propoxur and Methomyl are categorized from Carbamates. They inhibit acetylcholinesterase with reversible mode of action. They are less persistent with moderate toxicity. They have a wide spectrum against variety of weeds, insects and fungi. They are less severe than previous ones but still notable especially with repeated use (Cai *et al*., 2015).

Soil Persistence

They stay from short to moderate half-lives in terms of a few days to a few weeks. They are degraded like Organophosphates in the form of microbial activities, photolysis and hydrolytic mechanisms. They can be accumulated with less level at heterotrophs presented at food webs while they can still be leached under certain conditions (Berman *et al*., 2017).

Effects on Soil Microorganisms

They can inhibit beneficial microbes but at high concentrations. *Azospirillum* and *Rhizobium* as nitrogen-fixing bacteria from one side besides actinomycetes and *Bacilli* as microbial decomposers from another side are affected negatively with long-term or excessive use (Devi and Iyer, 2017).

Soil Enzyme Activity

The same key enzymatic proteins are inhibited by disturbance of nitrogen cycle, denaturation of microbial communities and alteration of phosphate availabilities for urease, dehydrogenase and phosphatase respectively.

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DOI:10.26502/ijabpt.202136

Soil Fauna Impact

Similarly, they impact on soil invertebrate fauna like earthworms, mites and nematodes and impair soil structure and aeration.

Pyrethroids

They are regarded as synthetic analogs of natural pyrethrins from *Chrysanthemum* sp. Cypermethrin, Deltamethrin, Lambda-cyhalothrin and Permethrin are common examples. They are distinguished with low toxicity to humans but have fast action and wide effects on soil ecosystems especially with frequent applications (Fareed *et al*., 2017).

Soil Persistence

Persistence and half-lives range from low to moderate as well as several days to a few months respectively. They are strongly adsorbed on soil particles especially in high organic matter or clay soils. Due to their low mobility, leaching to groundwater occur slowly (Hamada *et al*., 2015).

Effects on Soil Microorganisms

During repeated or high-dose applications of Pyrethroids treatments, they can suppress microbial activities and affect on beneficial bacteria like nitrogen fixers. They may cause temporary changes in microbial diversity with reversible action (Ishag *et al*., 2016).

Soil Enzyme Activity

They may reduce dehydrogenase, phosphatase and urease at microbial and plant combinations with delimitation of nutrient mineralization especially nitrogen and phosphorus cycles (Kulkarni and Kaliwal, 2018).

Soil Fauna Impact

They are highly toxic whether targeted or non-targeted invertebrates including earthworms, beetles and mites. They are able to change soil structure, aeration and organic matter composition (Omolo *et al*., 2012).

Environmental Considerations

They can bind tightly to soil particles besides accumulate around with repeated use. They are less toxic to mammals and birds but highly one to aquatic organisms if runoffs occur (Purushothaman and Kuttan, 2017).

Neonicotinoids

They affect insect nervous system on nicotinic receptors. They are systemic pesticides that used widely in seed treatments for complete removal of pests. Imidacloprid, Clothianidin, Acetamiprid, Dinotefuran and Thiamethoxam are common examples. They even affect beneficial insects like bees that decline the number and viability. They are called neonics because they are modeled from nicotine. They raise serious concerns for soil health and ecology due to their persistence and toxicity (Gabriela *et al*., 2024).

Soil Persistence

They are high persistence with different half-lives ranging from 100 to over 1,000 days depending on active compounds and soil conditions. For example, Imidacloprid is up to to 229–1,250 days while Thiamethoxam is similar to Clothianidin as long-lived duration. They moderately bind to soil particles however, they can still leach in sandy or low-organic soils (Zilli *et al*., 2020).

Soil Microorganisms

They are able to disturb soil microbial diversity particularly at activity level. They inhibit nitrogen-fixing bacteria, decomposers and fungi. They reduce soil respiration and nutrient cycling (Guimares *et al*., 2022).

Soil Enzyme Inhibition

All vital enzymes ar modified leading to slowly breakdown for organic matter and mineral availability (Chen *et al*., 2021).

Soil Fauna Impact

They are highly toxic to all types of minor organisms even Springtails and beneficial soil insects as well as they denature microbial population, soil structure and fertility (Onwona-Kwakye *et al.*, 2020).

Environmental Risk

They are systemic that can be absorbed by whole plant tissues including pollen grains and nectar glands. They can leach into groundwater smoothly. They are toxic to pollinators, aquatic life and possibly human health (Zhang *et al*., 2021).

Highlight closure

The insecticides have half-lives stability at soil structure. It influences on all types of microorganisms. The key enzymes are threated to be modified. Beneficial and non-beneficial invertebrates are affected. Leaching to groundwater is occurred (Fig:1).

Main Chemical Types of herbicides

Phenoxy Herbicides

They are categorized as herbicides such as Dicamba, 2,4-D (2,4-dichlorophenoxyacetic acid) and MCPA (2-methyl-4-chlorophenoxyacetic acid). They are selective commonly used to control broadleaf weeds in cereals and lawns by causing uncontrolled growth through mimic plant hormone stimulation. They have generally moderate soil impact. They cause environmental issues by improper use or long repetition **(Hiller *et al*., 2012)**.

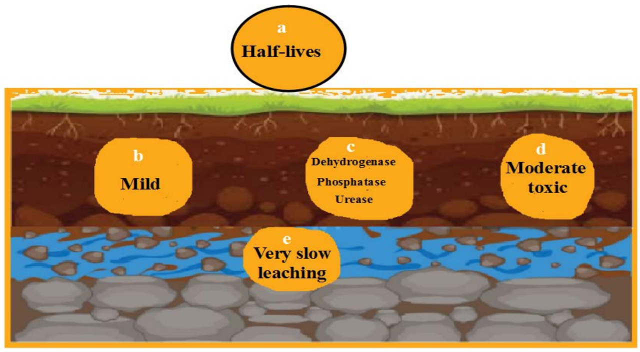

Figure 1: Diagrammatic scheme of insecticide effects on soils; a: soil persistence, b: soil microbes, c: soil enzymes, d: soil fauna, e: groundwater impact.

Soil Persistence

Half-life is between short to moderate typically 7 to 60 days depending on soil type, moisture, temperature and microbial activity. They are biodegradable by soil microbes that performed faster when conditions are warm and moist. They bind slowly to soil particles and penetrate downwards in light soils **(Farenhorst *et al.*, 2010)**.

Effects on Soil Microorganisms

At normal use levels, their effects are usually temporary and mild however, at high concentrations; they can reduce microbial activities, inhibit nitrogen-fixing bacteria and alter the balance of soil fungi and bacteria **(Janniche *et al.*, 2011)**.

Soil Enzyme Activity

They may inhibit dehydrogenase and urease briefly after applications however, enzyme activity can be recovered when herbicide degrades gradually **(Gaultier *et al.*, 2009)**.

Soil Fauna

Toxicity is low to moderate against earthworms and other soil invertebrates. They are usually non-lethal and short-lived unless misuse of application occurs **(Xu *et al.*, 2009)**.

Leaching Potential

Leaching risk is moderate especially in sandy or low-organic soils. They can contaminate groundwater if overused during heavy rains applies **(David *et al.*, 2013)**.

Triazines

They are Triazine herbicides such as Atrazine, Simazine, Propazine and Terbuthylazine that are widely used for controlling broadleaf and grassy weeds at Corn, sugarcane, and non-crop areas. They are known for their persistence and potential to contaminate soil and water. The main mode of action is inhibition of photosynthesis **(Jasmin *et al.*, 2011)**.

Soil Persistence

Half-life is long and ranges from 60 to over 300 days depending on atmospheric conditions. They bind moderately to soil particles especially in low-organic or sandy soils. There is a risk of accumulation with repeated use **(Rocha *et al.*, 2008).**

Effects on Soil Microorganisms

They inhibit all beneficial and non-beneficial soil microbes whether bacteria or fungi besides alter microbial balance and reduce microbial biomass **(Zhou *et al.*, 2006)**.

Soil Enzyme Activity

Phosphatase, urease and dehydrogenase are inhibited as well as Triazine herbicides decrease the rate of nutrient cycling and breakdown the organic matter **(Kolachi *et al.*, 2010)**.

Soil Fauna Impact

They may harm earthworms and other soil invertebrates. In addition, the soil fauna impact may be generally occurred according to dose-dependent and become more severe with prolonged use **(Afridi *et al.*, 2006)**.

Leaching and Environmental Risk

High leaching is occurred and detected at groundwater especially when treatment of atrazine is executed. Persistent is distinguished at low-organic soils and areas with heavy rainfall **(Katsumata *et al.*, 2006)**.

Bipyridyls

Bipyridyls, mainly Paraquat and Diquat, are fast-acting, non-selective, quick burndown contract herbicides. They are widely used but recognized as high toxic to humans and animals with strong soil interaction **(Nahim *et al.*, 2021)**.

Soil Persistence

They bind tightly to soil particles especially clay ones besides organic matter. They are chemically inactive once bound but residues can remain for years. Hence, they don't leach easily or even reach to groundwater **(Rasheed *et al.*, 2018)**.

Effects on Soil Microorganisms

Over time, microbial activity may recover after Bipyridyls treatments as the chemical compounds become immobilized but they are still harmful for all types of microorganisms **(Kaur *et al.*, 2016)**.

Soil Enzyme Activity

They can temporarily inhibit catalase enzyme in addition to urease and dehydrogenase. They are able to affect nutrient transformation and soil respiration **(Brigante *et al.*, 2013)**.

Soil Fauna

They are toxic to all forms of soil fauna like earthworms,

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DOI:10.26502/ijabpt.202136

insects and soil mites at application stages. Long-term impact is limited due to strong soil binding action **(Fortenberry *et al.*, 2016)**.

Environmental Considerations

They are highly toxic to humans and animals if ingestion or inhalation occur. Due to their immobilization, non-target plants can be injured and surface water may be contaminated if misapplied (**Al-Ghouti and Da'ana, 2020)**.

Ureas and Substituted Ureas

Ureas and substituted ureas (e.g. Diuron, Monuron, Linuron) are herbicides that are used as pre-emergence control in agriculture and forestry. The main action is to inhibit photosynthesis **(Ahmmed *et al.*, 2024)**.

Soil Persistence

The persistence is moderate to high with half-lives that range from 60 to more than 180 days. Diuron is especially persistent, lasting months under dry or cold conditions. Slow degradation is occurred in low-organic or low microbial soils **(Ni *et al.*, 2023)**.

Soil Microbial Impact

Nitrogen-fixing bacteria and microbial decomposers can be inhibited leading to microbial reduction besides slowed nutrient cycling **(Puga *et al.*, 2020)**.

Soil Enzyme Activity

Phosphatase, urease and dehydrogenase are affected and enzyme recovery is slow due to long persistence **(Ramalingappa *et al.*, 2023)**.

Soil Fauna

They are toxic to soil invertebrates, especially at high concentrations. Long-term exposure can decline earthworm populations **(Sangita *et al.*, 2018)**.

Leaching and Runoff Risk

Leaching potential is moderate to high in sandy or low-organic soils. They may contaminate groundwater or surface runoff especially after Diuron treatment **(Song *et al.*, 2020)**.

Dinitroanilines

Dinitroanilines (e.g.Trifluralin, Pendimethalin) are pre-emergence herbicides that widely used to control grasses and some broadleaf weeds in row crops and turf through inhibition of cell division by assembly action of microtubules. Their influence on soil is generally less mobile but can affect microbial and biological activities over time **(Jinyi *et al.*, 2021)**.

Soil Persistence

They stay at soil with moderate to high persistence. Half-life ranges from 45 to more than 180 days. Their affinity to soil organic matter and clay particle is very high. Low mobility tends to remain near to soil surface layer **(Soltani *et al.*, 2020)**.

Soil Microbial Impact

Soil microbial impact is minimal to moderate level. Higher or repeated doses can reduce microbial biomass and nitrogen-fixing bacteria **(Yu and Powles, 2014)**.

Soil Enzyme Activity

They can temporarily reduce dehydrogenase and phosphatase and impact negatively on microbial respiration and nutrient cycling **(Lyons-Abbott *et al.*, 2010)**.

Soil Fauna

They are toxic to earthworms and some beneficial insects located at soil surfaces. Long-term buildup may reduce soil biodiversity **(Chen *et al.*, 2019)**.

Leaching and Runoff Risk

Low leaching potential can be obtained due to strong absorption at soil textures. Runoff risk exists if they are applied before heavy rains on bare soil rocks **(Délye, 2013)**.

Glyphosate (Organophosphonate)

Glyphosate is a widely used non-selective, systemic herbicide. Though it degrades relatively quickly, it can still influence on soil health. by inhibition of EPSP synthase (shikimic acid pathways) **(Syrgabek and Alimzhanova, 2022)**.

Soil Persistence

Half-lives are short to moderate from 3 to 60 days. They bind strongly to soil particles, especially clay and organic matter. Low mobility present in moist soils but may persist longer in cold or low biological soils **(Thind *et al.*, 2018)**.

Microbial Impact

They can alter microbial communities by suppress nitrogenfixing bacteria and increase pathogenic fungi e.g. *Fusarium* sp. Some microbes can metabolize glyphosate as a phosphorus source **(Suwardji and Made, 2021)**.

Soil Enzyme Activity

They may temporarily reduce dehydrogenase, phosphatase and urease. Enzyme activity can be recovered over time **(Kanissery *et al.*, 2019)**.

Soil Fauna

Low toxicity directs to earthworms and insects while they affect indirectly on food chains and microbial disruption occurs (**Tarazona *et al.*, 2017)**.

Leaching and Runoff Risk

Low leaching present due to strong soil particle affinity,

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DOI:10.26502/ijabpt.202136

however, runoff in sediments can be done after heavy rains (**Wang *et al*., 2016**).

Sulfonylureas

Sulfonylurea herbicides (e.g. metsulfuron-methyl, chlorsulfuron, tribenuron-methyl) are low-dose, selective post-emergence control that inhibit ALS enzyme for amino acid synthesis. They can significantly influence soil health under certain conditions **(Timothy and Patrick, 2012)**.

Soil Persistence

Half-life is variable from 15 to more than 180 days. Longer persistence is remarkable in alkaline, dry or cold soils. They are more mobile in sandy or low-organic soils **(Berisford *et al*., 2006)**.

Microbial Impact

- At normal use rates: minimal impact

At normal use rates, there is minimal impact on soil structure. However, high or repeated doses may inhibit soil fungi and bacteria besides affect nitrogen-fixing microbes and reduce microbial diversity **(McCullough and Nutt, 2010)**.

Soil Enzyme Activity

They can suppress nitrate reductase, dehydrogenase and urease. They interfere with nitrogen and phosphorus cycling **(Matocha and Senseman, 2007)**.

Soil Fauna

Generally, they are considered as low toxicity against earthworms and insects. There are indirect effects that may occur from altered microbial food base **(Grey *et al*., 2007)**.

Leaching and Residual Effects

High mobility is found in high pH soils causing leaching risk to groundwater. They may injure sensitive crops in rotation if residues persist **(Maheswari and Ramesh, 2007)**.

Imidazolinones

Imidazolinone herbicides (e.g. imazapyr, imazethapyr, imazamox) are systemic, broad-spectrum herbicides in crops like rice, soybeans that inhibit branched-chain amino acid synthesis by induction of ALS inhibitor. Their influence on soil is notable due to persistence and potential for mobility **(Bundt *et al*., 2015)**.

Soil Persistence

Persistence is moderate to high with half-life ranges from 30 to more than 300 days. More persistent is present in alkaline soils with dry or low-organic conditions. They can remain active in soil for months. Negatively, they affect sensitive crops **(Arbeli and Fuentes, 2007)**.

Microbial Impact

They can alter microbial communities by different ways; they suppress beneficial fungi and bacteria, reduce *Rhizobium* distribution. Some microbial species can degrade Imidazolinones slowly **(Finlay, 2002)**.

Soil Enzyme Activity

They can inhibit dehydrogenase, urease and phosphatase and influence on diffusion of nutrient cycling and organic matter turnover **(Mangels, 1991)**.

Soil Fauna

Low direct toxicity is detected; however, long-term residues may reduce food sources for earthworms and soil insects **(Martinazzo, 2010)**.

Leaching and Carryover Risk

High mobility appears in sandy or alkaline soils. They can leach downwards to groundwater. Long residual activity may harm non-target crops in rotation time **(Vischetti, 2000).**

Glufosinate (Phosphinic Acid)

Glufosinate ammonium is a non-selective, contact herbicide used for post-emergence weed control for GM crops. Its mode of action is inhibition of glutamine synthetase (ammonia accumulation). Its influence on soil is generally limited compared to more persistent herbicides **(Xiaoyun *et al*., 2023)**.

Soil Persistence

Low persistence is accomplished with typical half-life from 3 to 25 days. Glufosinate ammonium is degraded rapidly by soil microbes. It binds moderately to soil particles so that limiting mobility is present **(Takano and Dayan, 2020)**.

Microbial Impact

At normal use, minimal effect on microbial populations is done. High doses may temporarily suppress nitrogen-fixing bacterial and fungal activity **(Yang *et al*., 2019)**.

Soil Enzyme Activity

Minor and short-term inhibition on dehydrogenase and phosphatase are recognized by using Glufosinate ammonium. Enzyme activity can be recovered quickly after breakdown process **(Bera and Ghosh, 2013)**.

Soil Fauna

Glufosinate ammonium has low toxicity against earthworms and beneficial insects. No significant long-term impact is occurred under recommended usage **(Zhu *et al*., 2015)**.

Leaching and Environmental Risk

Low leaching potential can be carried out especially in medium to high organic matter soils. Unlikely, groundwater can be contaminated under typical field conditions **(Shennan, 2008)**.

Benzoic and Carboxylic Acids

Benzoic and carboxylic acid herbicides (e.g. Dicamba, Picloram, 2,3,6-TBA) are synthetic auxins used to control broadleaf weeds as pasture management by inhibiting growth regulators. Their influence on soil depends on their specific chemical structure and environmental conditions **(Tamara *et al.*, 2022)**.

Soil Persistence

There is variable perisitence; Dicamba possess short to moderate from 1 to 60 days while Picloram is very persistent up to 1 year or more. As general, all benzoic and carboxylic acid herbicides have more persistent in dry, cold or low-organic soils **(Ransom *et al.*, 2014)**.

Microbial Impact

At normal rates, minimal microbial impact is occurred. Picloram can suppress microbial activity and degrade organic matter very slowly. Benzoic and carboxylic acid herbicides may slightly reduce bacterial diversity in some soils under different circumferences **(Bish *et al.*, 2019)**.

Soil Enzyme Activity

Temporary reduction at enzyme availability is occurred for dehydrogenase and urease. Enzyme levels can be recovered when the herbicide is broken down **(Silva *et al.*, 2020)**.

Soil Fauna

Earthworms and insects are toxin with low level. Moreover, Picloram may indirectly affect soil fauna by altering microbial balance **(Tropaldi *et al.*, 2021)**.

Leaching and Runoff Risk

Picloram possesses high leaching potential especially in sandy or alkaline soils. Moderate mobility of Dicamba can be executed at rain-prone areas **(Carbonari *et al.*, 2020)**.

Highlight closure

Soil persistence appears from short to half-lives while soil microbes are affected with medium level and reversible action may be done. Dehydrogenase and urease are denatured. Not all invertebrates are influenced however, leaching to groundwater is dangerous **(Fig. 2)**.

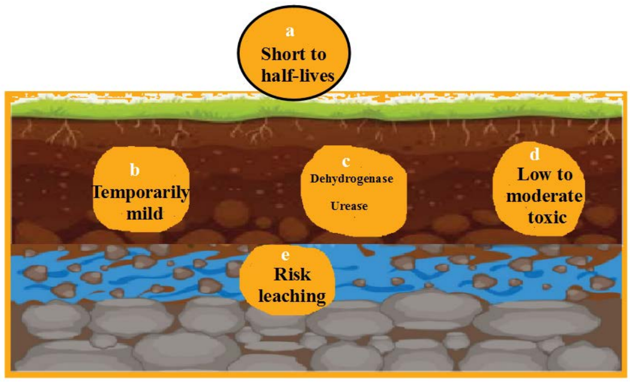

Figure 2: Diagrammatic scheme of herbicide effects on soils; a: soil persistence, b: soil microbes, c: soil enzymes, d: soil fauna, e: groundwater impact.

Main Chemical Types of fungicides

Benzimidazoles

Benzimidazole fungicides are primarily systemic fungicides that disrupt fungal cell division by tubulin interference and are used to control a wide range of plant pathogens at fruits, vegetables, cereals. Common examples include Benomyl, Carbendazim and Thiophanate-methyl. Their influence on soil profiles varies by application rate and frequency **(Radka, 2022)**.

Soil Persistence

Soil persistence is moderate where benomyl rapidly converts to carbendazim in soil structure. Half-lives range from 3 to 12 months, depending on soil type and conditions of irrigation **(Syslova *et al.*, 2019)**.

Effects on Soil Microorganisms

They are broad-spectrum antifungal agent that can suppress all types of fungi even beneficial ones like mycorrhizae besides soil bacterial communities. They may reduce fungal diversity and distort nutrient uptake and organic matter breakdown **(Podlipna *et al.*, 2021)**.

Soil Enzyme Activity

They inhibit major two key enzymes; dehydrogenase and phosphatase leading to temporary reduction in microbial activity and nutrient cycling **(Navratilova *et al.*, 2021)**.

Soil Fauna

Generally, low toxicity is recorded at Benzimidazole treatments against earthworms and non-target insects. Chronic use can cause subtle long-term effects on soil invertebrate distribution **(Dogra *et al.*, 2018)**.

Environmental Risk

Low leaching risk is remarkable due to moderate soil particle binding action. Breakdown products of Benzimidazole may still be bioactive or toxic **(Bisognin *et al.*, 2021)**.

Triazoles (DMI fungicides)

Triazoles (DMI fungicides) like tebuconazole, propiconazole and difenoconazole are systemic fungicides that inhibit fungal sterol biosynthesis in fungal membranes. They are broad-spectrum used at cereals, fruits and turf. Their influence on soil includes moderate persistence and impacts on microbial and enzymatic activity **(Anastasia *et al.*, 2023)**.

Soil Persistence

Soil persistence is moderate to high with half-life ranges

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from 30 to more than 400 days. It extends to be long period in cold, dry, alkaline or low-microbial soils. Triazoles combine to soil organic matter so that reducing mobility and increasing longevity are performed **(Roman *et al.*, 2021)**.

Microbial Impact

Triazoles can alter microbial community composition. They suppress beneficial fungi e.g. mycorrhizae. They may reduce bacterial activities at high doses treatment. Finally, overuse may lead to fungal resistance forming soil microbial imbalance **(Han *et al.*, 2019)**.

Soil Enzyme Activity

They inhibit all key enzymes; dehydrogenase, urease and phosphatase. They may impair nitrogen and phosphorus transformation **(Mohiddin *et al.*, 2021)**.

Soil Fauna

Low to moderate toxicity to earthworms and microarthropods is occurred. Indirect effects reduce microbial food sources **(Wachowska *et al.*, 2020)**.

Leaching and Environmental Risk

Low leaching potential is displayed due to soil binding action. Risk of residue buildup with repeated application can be done **(Lloyd *et al.*, 2021)**.

Strobilurins (QoI fungicides)

Strobilurins (e.g. Azoxystrobin, Pyraclostrobin, Trifloxystrobin) are broad-spectrum systemic fungicides that inhibit fungal mitochondrial respiration by action on cytochrome bc1 complex. Their influence on soil is important to consider due to persistence and microbial effects **(Rasha and Mohamed, 2021)**.

Soil Persistence

Moderate to high persistence is significant. Half-life ranges 30 to 200+ days. Persistence increases in low-organic, dry, or cold soils. Strobilurins bind strongly to soil particles, especially organic matter **(Feng *et al.*, 2020)**.

Microbial Impact

Strobilurins can reduce beneficial fungi, including mycorrhizal associations and decomposer fungi. They may affect bacterial diversity at higher concentrations. They alter microbial balance, especially with repeated use **(Hnátová *et al.*, 2003).**

Soil Enzyme Activity

Soil enzyme activity is suppressed. Dehydrogenase, urease and phosphatase are inhibited. Nutrient cycling and organic matter breakdown are controlled with negative impacts **(Isamu and Makoto, 2005).**

Soil Fauna

Low direct toxicity is exposed to earthworms and insects at field rates. Indirect impacts reduce microbial food base or enzyme shifts **(Balba, 2007)**.

Leaching and Runoff Risk

Low leaching potential is done due to strong adsorption on soil particles. Risk of surface runoff is accomplished if applied before heavy rain **(Rodrigues *et al.*, 2013)**.

Dithiocarbamates

Dithiocarbamates (e.g. mancozeb, zineb, thiram) are broad-spectrum, contact fungicides used widely on fruits, vegetables, and field crops. The mode of action is denaturation of effective multi-active sites of vital enzymes. Their influence on soil can be significant, especially with repeated use **(Claudia *et al.*, 2023)**.

Soil Persistence

It is low to moderate persistence. Three to seventy days are half-life range time. Dithiocarbamates are degraded faster in warm, moist, and biologically active soils. Breakdown can release toxic byproducts like ethylene thiourea (ETU) **(Catalina *et al.*, 2014)**.

Microbial Impact

Dithiocarbamates can suppress soil microbial populations, including: nitrogen-fixing bacteria and decomposer fungi. Long-term use may reduce microbial diversity and biomass **(Stadler *et al.*, 2022)**.

Soil Enzyme Activity

Dehydrogenase, phosphatase and urease are inhibited. Dithiocarbamates slow nutrient cycling and organic matter decomposition **(Öter and Zorer, 2021)**.

Soil Fauna

Dithiocarbamates are toxic to earthworms and nematodes, especially thiram. They can reduce soil invertebrate populations if overapplied **(Losacco *et al.*, 2022)**.

Leaching and Residue Risk

Generally low leaching is done. breakdown products like ETU are mobile and toxic. ETU is carcinogenic and can contaminate groundwater **(Caiel *et al.*, 2021)**.

Chloronitriles

Chloronitriles (mainly chlorothalonil) are broad-spectrum, protectant contact fungicides widely used in agriculture. They inhibit multiple metabolic pathways by deactivation of enzymes. Their influence on soil can be notable due to their chemical stability and impact on soil biology **(Małgorzata *et al.*, 2018)**.

Soil Persistence

It is moderate to high. Half-life is 30 - <120 days. There

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is strong binding between Chloronitriles and soil organic matter, especially in clay or humus-rich soils. Breakdown is slower in cool, dry, or low-microbial soils **(Shahgholi, 2014)**.

Microbial Impact

Toxicity is dispread into many soil microorganisms like fungi and nitrogen-fixing bacteria. There is a reduction at microbial diversity and a disturbance occurs at nutrient cycling **(Pimmata *et al.*, 2013)**.

Soil Enzyme Activity

Inhibition occurs at dehydrogenase, urease and phosphatase. Soil enzyme activity may be suppressed for soil fertility functions for weeks **(Oleszczuk *et al.*, 2014)**.

Soil Fauna

Earthworms and other invertebrates have been eliminated due to toxicity. Chronic exposure can reduce soil biological activity **(Srinivasulu and Rangaswamy, 2013)**.

Leaching and Environmental Risk

Low leaching is performed due to strong soil binding mechanism. However, toxic metabolites may accumulate in soil or enter runoff if misapplied **(Łozowicka *et al.*, 2016)**.

Phthalimides

Phthalimides, such as Captan and Folpet, are contact fungicides used mainly in fruit, seeds, ornamental and vegetable crops by interference with multi-active sites of major enzymes. Their influence on soil is generally short-term, but repeated or heavy use can impact soil biology **(Bernard *et al.*, 2022)**.

Soil Persistence

Low to moderate persistence and half-life of 3–30 days are occurred. Presence of rapid degradation is displayed by soil microbes and hydrolytic mechanical methods. Persistence increases in cold, dry, or low-biological activity soils **(Li *et al.*, 2022)**.

Microbial Impact

At normal application rates, minimal to moderate effects are present. High or repeated doses may suppress fungi more than bacteria as well as reduce temporarily microbial diversity **(Al-Jaroudi *et al.*, 2016)**.

Soil Enzyme Activity

Soil enzyme activity can be inhibited like dehydrogenase and phosphatase. These effects are usually short-lived **(Patil *et al.*, 2017)**.

Soil Fauna

Low toxicity to earthworms and soil insects is detected at standard doses. Some negative effects may occur at high concentrations or in sensitive soils **(Castro-Castillo *et al.*, 2013)**.

Leaching and Runoff Risk

Leaching potential is low while breakdown products generally bind to soil or degrade quickly **(Dempster and Luzzio, 2011)**.

Sulfur Compounds

Sulphur-based fungicides (e.g. elemental sulphur, lime sulphur, wettable sulphur) are traditional, broad-spectrum contact fungicides against Powdery mildew. They disturb fungal respiratory mechanisms. Their influence on soil is generally mild, but can accumulate with frequent use **(Ashish *et al.*, 2020)**.

Soil Persistence

Sulphur oxidizes in soil to sulfates (SO_4^{2-}) forming low persistence. Oxidation rate depends on moisture, temperature, and microbial activity **(Arvind *et al.*, 2018)**.

Microbial Impact

Mild microbial impact effects at normal doses are determined. High application rates can lower soil pH, suppress temporarily fungi and some bacteria and increase beneficial microbes like sulfur-oxidizing bacteria **(Kumar *et al.*, 2013)**.

Soil Enzyme Activity

Generally there is low soil enzyme impact that may slightly affect urease and phosphatase. On the other hand, Enzyme activity usually recovers quickly **(Singh *et al.*, 2015)**.

Soil Fauna

Low toxicity to earthworms and invertebrates is done while no significant long-term effects under standard use can be detected **(Rai and Singh, 2018)**.

Leaching and Environmental Risk

Low leaching potential is present. Sulfates formed are generally stable and part of natural sulfur cycling **(Girija *et al.*, 2020)**.

Copper-based Compounds

Copper-based compounds (e.g. copper sulfate, copper oxychloride, Bordeaux mixture) are widely used as fungicides and bactericides, especially in organic farming at fruits, vegetables and vineyards. They pose risks to soil health when overused because they may be accumulated in soil over time **(Martin *et al.*, 2025)**.

Soil Persistence

They are very persistent because copper mixtures aren’t degraded. Accumulation at soil profile is observed with

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repeated applications. Long-term buildup can lead to copper toxic percentage **(Tseng *et al.*, 2021)**.

Effects on Soil Microorganisms

They are broad spectrum for all types of microorganisms whether beneficial or not that reduce microbial biomass and diversity over time **(Vazquez-Blanco *et al.*, 2020)**.

Soil Enzyme Activity

All key enzymes are inhibited with remarkable reduction of soil respiration and slower nutrient cycling **(Wang *et al.*, 2022)**.

Soil Fauna

High concentrations impair soil structure and aeration resulting from their high toxicity against all soil fauna members **(Zhao *et al.*, 2022)**.

Soil Properties

Copper mixtures bind strongly to clay particles and organic matter but excessive buildup may be occurred. Consequently, they alter soil PH and cation exchange capacilty. They interfere deeply with plant nutrient uptake especially iron and zinc **(You *et al.*, 2018)**.

Highlight closure

Fungicides stay medium period. They infect all types of microorganisms while not all key enzymes are affected. Similarly, not all invertebrates are killed. The rate of fungicide molecules penetration is not dangerous **(Fig. 3)**.

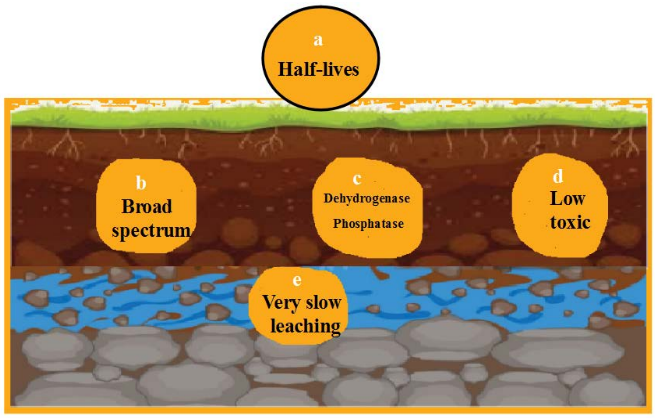

Figure 3: Diagrammatic scheme of fungicide effects on soils; a: soil persistence, b: soil microbes, c: soil enzymes, d: soil fauna, e: groundwater impact.

Main Chemical Types of bactericides

Copper-Based Bactericides

Copper-based bactericides (e.g. copper hydroxide, copper sulfate, copper oxychloride and Bordeaux mixture) act similarly to copper fungicides by denaturing proteins and enzymes in bacteria using in fruits, vegetables, and vineyards. When used repeatedly, they accumulate in the soil and can significantly affect soil biology and quality **(Yue *et al.*, 2023)**.

Soil Persistence

Copper is a heavy metal and non-degradable creates very high persistence. It remains in soil for years to decades. It binds to organic matter and clay, limiting mobility but not toxicity **(Marckmann *et al.*, 2019)**.

Microbial Impact

It is broad-spectrum toxicity to soil microbes as it inhibits nitrogen-fixing bacteria (e.g. *Rhizobium*). It reduces nitrifiers, decomposers, and overall microbial diversity. Repeated use can cause long-term shifts in microbial balance **(Straw *et al.*, 2018)**.

Soil Enzyme Activity

Strong inhibition of dehydrogenase, urease and phosphatase with slow rate of nutrient cycling and reduced soil fertility **(Tarakanov *et al.*, 2023)**.

Soil Fauna

It is toxic to earthworms, springtails, and beneficial nematodes. Accumulation may result in chronic toxicity and biodiversity loss **(Sadek *et al.*, 2022)**.

Leaching and Environmental Risk

Low leaching in most soils is found. Risk of runoff into waterways, where copper is toxic to aquatic life **(Aien *et al.*, 2023)**.

Quaternary Ammonium Compounds (QACs)

Quaternary ammonium compounds (QACs) e.g. benzalkonium chloride, didecyldimethylammonium chloride (DDAC) are disinfectants, surface sterilants bactericides often used in agriculture not typically applied directly to crops, greenhouses, and livestock settings. They disturb bacterial cell membranes. Their influence on soil depends on usage intensity and soil type **(Ines *et al.*, 2018)**.

Soil Persistence

It is moderate to high persistence that can last days to weeks. It strongly adsorbs to clay and organic matter, reducing mobility but potentially accumulating with repeated use **(Ding *et al.*, 2013)**.

Microbial Impact

It acquires with broad-spectrum antimicrobial action through killing Gram-positive and Gram-negative bacteria and suppressing beneficial microbes (e.g. *Rhizobium*, *Pseudomonas*). It can significantly reduce microbial biomass and diversity with overuse **(Droge and Goss, 2013)**.

Soil Enzyme Activity

It may inhibit dehydrogenase and urease. It destroys nutrient cycling, especially nitrogen transformation **(Ertekin *et al*., 2016)**.

Soil Fauna

It is toxic to soil invertebrates (e.g. earthworms, nematodes) at high doses. Indirect effects may be carried out from disrupted microbial food sources **(Fo¨rster *et al*., 2008)**.

Leaching and Environmental Risk

Low leaching may be appeared due to strong soil binding action. Risk of runoff to water bodies is executed besides QACs are toxic to aquatic organisms **(Fraise, 2011)**.

Silver-Based Compounds

Silver-based bactericides (e.g. silver nitrate, silver nanoparticles) are effective for experimental or high-value crops against a wide range of microbes by integrity within DNA replication and enzyme function, but their influence on soil can be significant due to their persistence and toxicity **(Tsepina *et al*., 2022)**.

Soil Persistence

High persistence is translated into no degradation, especially in metallic or nanoparticle form. Silver components bind strongly to organic matter and clay, but remain biologically active **(Neukum, 2018)**.

Microbial Impact

It is highly toxic and impact to soil microbes by enabling aseptic conditions against bacteria, fungi and actinomycetes. It inhibits nitrifiers, nitrogen-fixers, and decomposers as well as it reduces microbial diversity and enzyme production **(Braun *et al*., 2015)**.

Soil Enzyme Activity

Strong inhibition is occurred of dehydrogenase, urease and phosphatase. It slows nutrient cycling and organic matter decomposition **(Hedberg *et al*., 2015)**.

Soil Fauna

It is toxic to earthworms, nematodes, and microarthropods. It can bioaccumulate and cause long-term soil ecosystem imbalance **(Savignan *et al*., 2023)**.

Leaching and Environmental Risk

Low mobility is present for silver molecules, but they may leach under certain conditions (e.g. low pH, high salt). It is very toxic to aquatic organisms if runoff occurs **(Rehan *et al*., 2017)**.

Highlight closure

On contrary, bactericides have permanent persistence with severe aseptic against wide number of microbes. All types of soil enzymes are denatured. The degree of toxicity spread all types of invertebrates however, the rate of fungicide molecules penetration is limited **(Fig. 4)**.

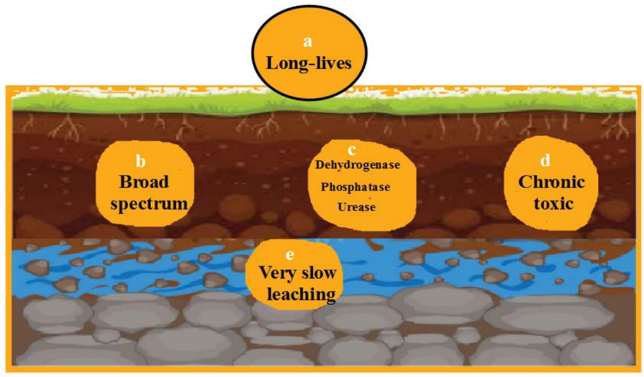

Figure 4: Diagrammatic scheme of bactericide effects on soils; a: soil persistence, b: soil microbes, c: soil enzymes, d: soil fauna, e: groundwater impact.

Main Chemical Types of viricides

Viricides (antiviral agents for plants) are fewer and less specific than fungicides or bactericides. They mainly work by inhibiting viral replication, inducing plant resistance, or inactivating viruses directly.

Ribavirin-Like Compounds

Ribavirin-like compounds like thiouracil derivatives (broad-spectrum antiviral agents) are not widely used as viricides in agriculture, but their analogs may be tested or studied for plant virus control by inhibiting viral RNA synthesis or replication. If applied to soil or released through treated plant residues. It is limited use in plants due to toxicity and cost **(Xiaohui *et al*., 2024)**.

Soil Persistence

Soil persistence is moderate that may remain for days to weeks. Ribavirin-like compounds are subjected to degradation by soil microbes and hydrolysis. Persistence varies with temperature, pH, and microbial activity **(Karjadi and Karjadi, 2022).**

Microbial Impact

Ribavirin-like compounds can affect RNA-dependent processes in soil microbes that may suppress beneficial bacteria (e.g. *Rhizobium*, *Pseudomonas*), some fungi and actinomycetes. Broad-spectrum activity could alter microbial balance **(Morales-Paredes *et al*., 2022)**.

Soil Enzyme Activity

Soil enzyme activity is potential to be inhibited nucleic acid-related enzymes in microbes. Ribavirin-like compounds may reduce dehydrogenase and urease activity temporarily **(Shang *et al*., 2019)**.

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Soil Fauna

There is limited data for soil fauna impact by Ribavirin-like compounds but they are potential for low to moderate toxicity to soil invertebrates. Risk increases with repeated exposure or high concentrations **(Shi *et al*., 2018)**.

Leaching and Environmental Risk

Low to moderate leaching is obtained, depending on solubility and soil type. Possible contamination of water sources is occurred if applied in large volumes or poorly managed **(Su *et al*., 2023)**.

Nanoparticles

Nanoparticle-based viricides (e.g. silver, zinc oxide, copper oxide, chitosan, silica nanoparticles) are emerging tools for plant virus control by interfering with virus particles or replication. Their influence on soil depends on the type, concentration, and frequency of use. It is a new approach that is experimental and increasingly studied in plant virology **(Joanna *et al*., 2024)**.

Soil Persistence

High persistence is present especially for metal-based nanoparticles (Ag, Cu, Zn) that are considered as non-degradable and may accumulate in soil over time **(Kulthong *et al*., 2010)**.

Microbial Impact

Nanoparticle-based viricides have broad-spectrum antimicrobial and antiviral effects by inhibiting virus-infected plant residue decomposition and kills bacteria, fungi, and actinomycetes. They reduce microbial diversity and interfere with nitrogen cycling **(El Badawy *et al*., 2010)**.

Soil Enzyme Activity

Dehydrogenase, urease and phosphatase are inhibited after Nanoparticle-based viricides usage. They disrupt nutrient cycling and organic matter decomposition **(Klitzke *et al*., 2015)**.

Soil Fauna

They are toxic to earthworms, nematodes, and microarthropods at high doses. Bioaccumulation risk in soil organisms with repeated application is done **(Pachapur *et al*., 2016)**.

Leaching and Environmental Risk

Low mobility is the property of nanoparticle-based viricides but may be leached as ions (e.g. Ag^{+}, Zn^{2+}) under acidic or saline conditions. They are generally toxic to aquatic life if runoff occurs **(Vance *et al*., 2015)**.

Highlight closure

The soil persistence is limited range period. Viricides have vigorous effect on all types of microorganisms besides virus and viroids. The key enzymes have limited effect. Although microorganisms are more affected, viricides are little effective on macroorganisms. Groundwater is affected with medium level **(Fig. 5)**.

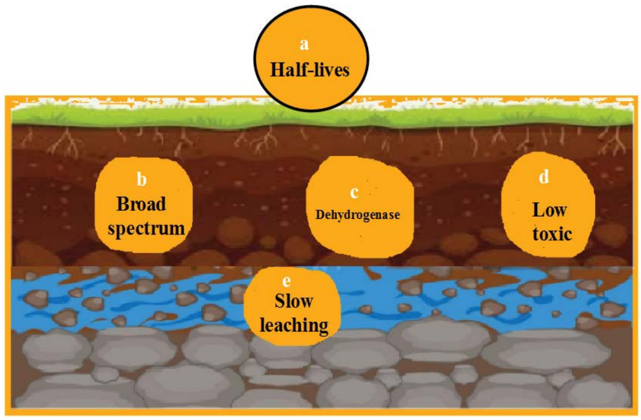

Figure 5: Diagrammatic scheme of viricde effects on soils; a: soil persistence, b: soil microbes, c: soil enzymes, d: soil fauna, e: groundwater impact.

Conclusion

The chemical pesticides have negatively effects on soil structure whether physical impacts presenting at leaching property to groundwater, chemical impacts representing at different chemical structure and chelation abilities as well as biological impacts representing at microbial and fauna denaturation. Alternative pesticides should be used nowadays for conserving environment from more unhealthy impacts. Natural products or semi-synthetic presides are suggested solutions to carry out the target of pathogen elimination besides safety tools for all abiotic factors like air, water and soils.

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