Pesticide-Induced Decline of Soil Arthropods: Ecological Consequences and Implications for Sustainable Agriculture

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ABSTRACT

Pesticides comprise both naturally derived and synthetically manufactured compounds extensively employed to control insects, weeds, fungi, rodents, nematodes, and other agricultural pests. Their widespread application has significantly enhanced crop productivity and food security; however, indiscriminate use has resulted in serious environmental and public health concerns. Owing to their toxic nature, pesticides can adversely affect living organisms, and the World Health Organization (WHO) classifies these compounds according to their potential health hazards. This article provides a comprehensive review of pesticides' global distribution, classification, applications, and environmental effects. It summarizes the available literature on pesticide classification based on source, chemical composition, mode of action, target organisms, and toxicity. Furthermore, the review discusses the detrimental effects of pesticide residues on terrestrial and aquatic ecosystems, soil and water quality, plant physiology, metabolism, defence mechanisms, genotypic and phenotypic characteristics, and human health, including their association with genetic alterations, carcinogenesis, allergic disorders, and respiratory diseases. Eco-friendly approaches for pesticide remediation, such as bacterial degradation, mycoremediation, phytoremediation, and microalgae-based bioremediation, are highlighted. These biological systems utilize diverse catabolic enzymes to degrade pesticide residues and facilitate environmental detoxification. The review also emphasizes the need to identify efficient microbial strains, novel degradative genes, and advanced biotechnological strategies to achieve sustainable pesticide waste management.

Keywords: Pest, Bio-magnification, Safe level, DDT, Target Pesticides, Macro-arthropods & Micro-arthropods

INTRODUCTION

Soil arthropods are integral components of terrestrial ecosystems, contributing significantly to ecosystem functioning through their diversity, abundance, and ecological activities. These organisms play crucial roles in sustaining soil fertility by aiding in the breakdown of organic matter, nutrient cycling, and the establishment of stable soil structure. Diverse groups of soil arthropods, including mites, springtails, termites, isopods, and other soil-dwelling invertebrates, fragment and decompose plant and animal residues, thereby accelerating the recycling of essential nutrients such as nitrogen and phosphorus that support plant growth. Their burrowing and tunnelling activities improve soil aeration, porosity, aggregate stability, and water infiltration, ultimately enhancing soil productivity and minimizing erosion. Consequently, the conservation of soil arthropod diversity is fundamental for sustaining soil quality, agricultural productivity, and overall ecosystem stability [1 - 3].

Soil health is governed by the interactions among soil biota, physicochemical characteristics, and the availability of essential nutrients [4]. Because of their high sensitivity to environmental disturbances and agricultural management practices, soil arthropods are widely recognized as reliable bio indicators of soil quality and ecosystem health [5, 6]. Variations in their abundance, diversity, and community composition provide valuable information regarding the biological responses of soil to environmental changes [7]. Furthermore, the presence of specific arthropod taxa has been positively correlated with improved soil health [6]. The ecological adjustment of soil arthropods to their environment can be assessed by the Qualità Biologica del Suolo (QBS) approach, commonly referred to as the Biological Index of Soil Quality. This method utilizes an Eco-Morphological Index (EMI) spanning from 1 to 20, which is founded on morphological traits such pigmentation, appendage evolution, vision systems, and body dimensions, to evaluate the level of arthropod specialization to the soil habitat. Pesticides are naturally derived or synthetically produced chemical compounds used to prevent, suppress, or eliminate insects, weeds, fungi, bacteria, viruses, nematodes, and other organisms that adversely affect agricultural productivity. These compounds are commonly classified according to their source, chemical structure, mode of action, target organisms, and application methods [8,9]. While pesticides have been essential in enhancing agricultural output by mitigating crop losses due to pests, illnesses, and weeds [10,11], their indiscriminate and excessive use has become a major environmental concern. Persistent pesticide residues contaminate soil, water, air, fruits, vegetables, and processed food products, posing serious risks to both ecosystems and human health [12]. Exposure to pesticides through occupational activities or contaminated food has been associated with acute and chronic health disorders, particularly in developing countries. Several chemical pesticides exhibit carcinogenic, mutagenic, and cytotoxic properties, thereby posing significant public health challenges [13]. A collaborative report from the World Health Organization (WHO) and the United Nations Environment Program (UNEP) indicates that around three million instances of pesticide poisoning and close to 200,000 fatalities linked to pesticides transpire worldwide annually, predominantly in developing countries [14].

Despite their undeniable contribution to modern agriculture, the extensive use of chemical pesticides has raised growing concerns regarding their adverse effects on non-target organisms, particularly soil arthropods that play essential roles in maintaining soil ecosystem functions. Changes in the diversity and population of soil arthropods can interfere with nutrient cycling, organic matter breakdown, soil structure development, and several ecological functions, eventually influencing long-term soil fertility and ecosystem viability. Consequently, comprehending the relationships between pesticides and soil arthropod populations is crucial for formulating environmentally sustainable pest control methods that enhance agricultural yield while reducing ecological harm [15 - 17].

Scope and Objectives of This Review

This review has three primary objectives: (1) to synthesise the available evidence on the effects of pesticide exposure on soil arthropod populations, including both macro-arthropods and micro-arthropods; (2) to evaluate the ecological consequences of pesticide-induced arthropod decline for soil ecosystem functioning; and (3) to identify knowledge gaps and research priorities for understanding pesticide-arthropod interactions in the context of sustainable agriculture. While the review provides necessary background on pesticide classification and environmental fate, the primary focus is on the effects of pesticide exposure on soil arthropod communities and the implications for soil health and ecosystem services.

Pest, Pest Control, and Pesticides

A pest is any organism that causes economic damage or adversely affects human activities, agriculture, forestry, livestock, or public health. It may be a plant, animal, or microorganism that directly or indirectly interferes with crop production, stored products, domestic animals, or natural ecosystems. Common examples of destructive animal pests include birds, rats, mice, rabbits, and numerous insect species.

Need for Pest Control

Effective pest management has become increasingly important due to the growing global demand for food and agricultural products. The World Health Organization (WHO) estimates that nearly one-third of the global population is afflicted by hunger and malnutrition. As the human population expands, agricultural production must increase substantially to satisfy rising food requirements. However, pests remain one of the major constraints to sustainable crop production, causing significant losses both in the field and during post-harvest storage. Therefore, effective pest control measures are essential to minimize crop damage, improve agricultural productivity, and ensure global food security [18].

Pest Control

Pest control refers to the regulation or management of organisms considered harmful to humans, crops, livestock,

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or the environment [20]. Depending on the nature of the pest and the production system, different management approaches may be adopted either individually or in combination [19]. The principal methods of pest control include:

- Agro-technical control
- Mechanical control
- Biological control
- Chemical control, which constitutes one of the major components of integrated pest management programmer.

Classification of Pests

Pests comprise a wide range of organisms capable of causing damage to agricultural crops, domestic animals, stored products, and human health. They are broadly classified into the following categories [19]:

1. Insects (e.g., aphids, beetles, and whiteflies)
2. Rodents (e.g., rats and mice)
3. Weeds (e.g., dandelions and thistles)
4. Fungi (e.g., powdery mildew and rust fungi)
5. Bacteria (e.g., leaf spot- and blight-causing bacteria)
6. Viruses (e.g., Tobacco mosaic virus)
7. Nematodes (microscopic parasitic roundworms)

Pesticides

The term pesticide is derived from the words pest (a harmful organism) and -cede (to kill). Pesticides are natural or synthetic chemical substances used to eliminate, suppress, repel, or control organisms that adversely affect agricultural production, public health, or stored commodities. Depending on their intended use, pesticides include insecticides, herbicides, fungicides, rodenticides, nematicides, and several other specialized formulations [19].

Properties and Characteristics of Pesticides

Pesticides possess several physicochemical and biological characteristics that determine their effectiveness as well as their environmental behaviour [21].

1. Owing to their inherent toxicity, pesticides function as environmental contaminants and may adversely affect both target and non-target organisms.
2. Most conventional pesticides possess relatively simple chemical structures and exhibit specific biological activities against particular groups of pests.
3. The toxicity of a pesticide is commonly expressed by its median lethal dose (LD_{50})**,** which represents the dose required to cause mortality in 50% of the test population under defined experimental conditions.
4. Many pesticides are capable of moving through food chains, resulting in bio magnification and the accumulation of toxic residues at higher trophic levels [22].
5. Several synthetic pesticides are highly persistent and resistant to biodegradation, allowing them to remain active in the environment for prolonged periods [22, 23].
6. During degradation, certain pesticides may produce secondary metabolites that are more toxic than the parent compounds, thereby posing additional ecological and health risks.

Safe Level of Pesticides

The safe level of a pesticide refers to the maximum concentration at which exposure does not produce significant adverse effects on target or non-target organisms within an ecosystem. In practical terms, it represents a concentration that causes no observable biological effects or only a minimal and acceptable level of impact (generally $\leq$5%) on non-target species while ensuring effective pest management.

Classification of pesticides:-

Pesticides are categorized on the basis of four primary structural and functional criteria (Table 1): [24]

Table 1: Classification of pesticides based on primary structural and functional criteria

1. On the Basis of Source	2. Target Pesticide	3. Mode of Action	4. Chemical Structure
Natural: Nicotine, Pyrethrum, Neem oil, Boric acid, Rotenone **Synthetic:** DDT, Aldrin, Dieldrin, Malathion, Parathion	Insecticides Herbicides Fungicides Rodenticides Nematicides Algicides Ovicides	Stomach Poison Contact Poison Fumigants • Systemic Pesticides	**Organochlorines:** DDT, BHC **Organophosphates:** Parathion, Malathion **Carbamates:** Carbofuran, Carbaryl **Quinones:** Chloranil **Anilides:** Alachlor, Butachlor

Classification of Pesticides Based on Their Source

Pesticides are broadly categorized into natural and synthetic pesticides depending on their origin.

A. Natural Pesticides [19]

Natural pesticides are biologically derived compounds obtained from plants, animals, microorganisms, or naturally occurring minerals. These substances possess pesticide properties and are generally considered environmentally compatible alternatives to synthetic chemicals.

Nicotine: Nicotine is a naturally occurring alkaloid extracted from the leaves and stems of the tobacco plant (Nicotiana tabacum). It acts as a potent neurotoxin that rapidly disrupts the nervous system of insects and has been extensively used for the control of sap-sucking pests such as leafhoppers. [19]

Pyrethrum: Pyrethrum is obtained from the dried flower heads of Chrysanthemum (Pyrethrum) species. The flowers are harvested, dried, powdered, and extracted with suitable organic solvents to isolate pyrethrums, the biologically active compounds. Pyrethrum acts as a rapid contact insecticide and is effective against flies and numerous other flying insects. It has been reported to control more than 40 insect species affecting over 200 fruit and vegetable crops (25 - 28).

Boric Acid (H_3BO_3): Boric acid is a naturally occurring inorganic mineral widely used as an effective pesticide against cockroaches, ants, and several microorganisms owing to its toxic effects following ingestion. [19]

Rotenone: Rotenone is a naturally occurring crystalline compound isolated primarily from the roots of leguminous plants such as Derris elliptica (29). Owing to its insecticidal and piscicidal properties, it has historically been employed for pest management and fish control.

B. Synthetic Pesticides

Synthetic pesticides are chemically manufactured compounds produced through industrial chemical synthesis. Their high efficacy, prolonged residual activity, and relatively low production costs have contributed to their widespread application in modern agriculture.

Common examples include dichlorodiphenyltrichloroethane (DDT), β-hexachlorocyclohexane (BHC), aldrin, dieldrin, endrin, chlordane, parathion, captan, and 2,4-dichlorophenoxyacetic acid (2,4-D) [30].

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Historical Perspective of DDT

Dichlorodiphenyltrichloroethane (DDT) is one of the most extensively studied synthetic insecticides in history (22). Following its introduction, DDT became a cornerstone of agricultural pest control and vector management because of its remarkable effectiveness against gypsy moths, Japanese beetles, mosquitoes, and numerous other insect pests. Consequently, its application increased rapidly in agricultural systems worldwide (31).

Despite its effectiveness, DDT was later recognized as a persistent organic pollutant. Due to its resistance to biodegradation, it accumulated in living organisms and underwent bio magnification through food chains, causing severe ecological damage and posing risks to wildlife and human health. As a result, the United States prohibited its agricultural use in 1972, and many other countries subsequently imposed similar restrictions.

Major groups of synthetic pesticides include:

- Organochlorines: DDT, BHC, Gammexane (31)
- Organophosphates: Malathion, Parathion (23)
- Carbamates: Carbofuran, Carbaryl (32)

2. Classification of Pesticides Based on Target Organisms

Depending on the organisms they are intended to control, pesticides are classified into several functional groups.

Insecticides

Insecticides are designed to control insect pests such as aphids, beetles, whiteflies, and other economically important insects. Common classes include organophosphates, pyrethroids, and carbamates (33).

Herbicides

Herbicides are applied to eliminate or suppress undesirable plants (weeds) that compete with cultivated crops for nutrients, water, and light. Glyphosate and atrazine are among the most widely used herbicides (34).

Fungicides

Fungicides are employed to prevent or control fungal diseases affecting agricultural crops by inhibiting fungal growth and development. Chlorothalonil and triazole compounds are widely used examples (35).

Rodenticides

Rodenticides are formulated to manage rodent pests such as rats and mice, which damage crops and stored food products and transmit several diseases. Common rodenticides include warfarin and bromadiolone (36).

Bactericides

Bactericides are used to suppress or eliminate bacterial pathogens infecting plants and animals. Streptomycin and copper sulphate are among the commonly used bactericidal agents.

Nematicides

Nematicides are specifically developed to control plant-parasitic nematodes, thereby protecting crop productivity. Carbofuran and soil fumigants represent commonly used nematicidal compounds (37 - 39).

Ovicides

Ovicides are pesticides that target and destroy the eggs of insects and mites before hatching, thereby interrupting their life cycle and reducing future pest populations. Synthetic compounds such as diflubenzuron are widely employed as ovicidal agents (40, 41).

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Classification of Pesticides Based on Their Mode of Action

Pesticides can be classified according to the mechanism by which they exert toxic effects on target organisms. Based on their mode of action, they are categorized into the following groups:

1. Stomach Poisons

Stomach poisons produce their toxic effects after being ingested by the target organism. These pesticides must enter the digestive tract along with the food consumed by the pest. Following ingestion, the active compounds are absorbed through the gut epithelium during digestion and subsequently distributed throughout the body, resulting in systemic toxicity and eventual death of the pest (42). Representative examples include BHC and DDT.

2. Contact Poisons

Contact poisons kill insects through direct contact with the external body surface. The active ingredients penetrate the insect cuticle or exoskeleton and enter the haemolymph, from where they are transported to their target tissues, particularly the nervous system, leading to paralysis and mortality (43). Common examples include DDT and BHC.

3. Fumigants

Fumigants are volatile pesticides that act through the respiratory system of target organisms. They are applied in gaseous or vapour form and enter the body through the spiracles and tracheal system, where they interfere with normal physiological functions, resulting in rapid mortality (44). Typical fumigants include hydrogen cyanide (HCN), carbon disulphide (CS_2), and highly volatile nicotine formulations.

4. Systemic Pesticides

Systemic pesticides are absorbed by plant tissues through the roots, stems, or leaves and subsequently translocate via the vascular system without causing injury to the host plant. Herbivorous insects ingest these pesticides while feeding on treated plant tissues, leading to poisoning and death (45). Because of their internal distribution within the plant, systemic pesticides provide prolonged protection against sap-feeding and chewing insect pests.

Classification of Pesticides Based on Chemical Structure [19]

According to their chemical composition, pesticides are broadly divided into inorganic and organic compounds.

A. Inorganic Pesticides

Inorganic pesticides are mineral-based compounds that generally lack a carbon-hydrogen skeletal framework. They are primarily composed of inorganic salts, heavy metals, sulphur-containing compounds, or halogen-based formulations. These compounds have historically been used for pest control, although many have been replaced by safer alternatives due to concerns regarding environmental persistence and toxicity.

Examples: Lead arsenate and calcium arsenate.

B. Organic Pesticides

Organic pesticides possess carbon-based molecular structures and constitute the largest group of pesticides used in agriculture. Depending on their origin, they are further classified into natural organic pesticides and synthetic organic pesticides.

Natural Organic Pesticides: These pesticides are obtained directly from biological sources such as plant extracts, essential oils, flowers, leaves, roots, stems, seeds, and microbial metabolites.

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Synthetic Organic Pesticides: These are chemically synthesized compounds that can be grouped according to their chemical structures and functional groups.

- Organochlorines: Chlorinated hydrocarbon compounds characterized by high chemical stability and environmental persistence (31).
- Organophosphates: Phosphoric acid derivatives that exhibit high insecticidal activity by inhibiting acetylcholinesterase and disrupting nerve impulse transmission (30).
- Carbamates: Compounds derived from carbamic acid that exert insecticidal activity through reversible inhibition of acetylcholinesterase (30).

Soil Arthropods

Soil forms the fundamental basis of terrestrial ecosystems and serves as the primary medium supporting plant growth and agricultural productivity. Soil fertility refers to the ability of soil to supply vital nutrients and create a conducive environment for ongoing plant development and reliable crop yield. Among the diverse soil biota, soil arthropods represent one of the most important biological components, contributing significantly to soil health, fertility, and ecosystem functioning. These organisms perform a wide range of ecological functions, including the decomposition of organic matter, nutrient mineralization, soil aeration, and the regulation of microbial communities. Through the fragmentation of plant litter and other organic residues, soil arthropods accelerate decomposition and facilitate the recycling of essential nutrients required for plant growth. In addition, many arthropods act as natural predators of soil-dwelling pests, thereby contributing to the biological regulation of pest populations. Their burrowing and tunnelling activities enhance soil porosity, water infiltration, aggregation, and moisture retention, which collectively improve soil structure and reduce erosion. Consequently, soil arthropods are recognized as indispensable indicators of soil quality, and their conservation is essential for maintaining healthy and sustainable terrestrial ecosystems [46].

Classification of Soil Macro-organisms [47 - 50]

Based on taxonomic characteristics, soil macro-organisms are broadly classified into three major phyla:

1. Phylum Annelida

- Earthworms
- Pot worms

2. Phylum Arthropoda

Macro arthropods

- Springtails (Collembola)
- Mites (Acarina)
- Ants (Formicidae)

Micro arthropods

- Isopods (woodlice)
- Chilopods (centipedes)
- Diplopods (millipedes)
- Soil-dwelling spiders
- Larvae and adults of various insects, including beetles and wireworms

3. Phylum Mollusca

- Slugs
- Snails

The diversity of these soil organisms contributes to numerous ecological processes that regulate soil productivity and ecosystem stability. Alterations in their abundance and diversity may therefore serve as sensitive indicators of environmental disturbances, particularly those associated with agricultural practices and pesticide application.

Effects of Pesticides on Soil Micro arthropods

Soil micro arthropods are highly sensitive to pesticide exposure and are frequently used as biological indicators for assessing soil contamination. These organisms play essential roles in decomposition, nutrient cycling, and maintaining soil biodiversity. Consequently, alterations in their abundance, behaviour, physiology, and reproductive performance can adversely affect overall soil ecosystem functioning. [51 - 53]

Diplopoda (Millipedes)

Millipedes (Class: Diplopoda) are important decomposers that facilitate the breakdown of organic matter and contribute to nutrient recycling within terrestrial ecosystems. Several studies have demonstrated that exposure to pesticides adversely affects both their survival and physiological performance. Deltamethrin significantly reduced survival and impaired neurological functions in millipedes, leading to behavioural abnormalities such as excessive agitation, secretion of defensive fluids, externalization of gonopods, and haemolymph leakage (54). Likewise, exposure to diflubenzuron and mancozeb resulted in a marked decline in myriapod populations. Similarly, carbendazim and lambda-cyhalothrin substantially reduced the abundance of the millipede Trigoniulus corallinus (Gervais), indicating the susceptibility of these decomposers to pesticide contamination [55, 56].

Isopoda (Woodlice)

Woodlice (Order: Isopoda) are another important group of soil detritivores that contribute significantly to organic matter decomposition. Numerous pesticides adversely influence their behaviour, physiology, and reproductive performance (57, 58). Exposure to pesticides reduced feeding activity, faecal pellet production, locomotion, and avoidance behaviour, while simultaneously disrupting metabolic and enzymatic functions. Growth and reproductive success of isopods were significantly impaired following exposure to dimethoate and lambda-cyhalothrin. Furthermore, imidacloprid caused a significant reduction in the epithelial thickness of Porcellio scaber, indicating structural damage to internal tissues. These findings collectively demonstrate that pesticide exposure compromises both the physiological integrity and ecological functions of isopod populations [59 - 61].

Beetles and Other Soil-Dwelling Insects

The larval and adult stages of numerous soil-dwelling insects, including beetles (Order: Coleoptera) and wireworms, are also adversely affected by pesticide application (62). Pesticide exposure has been associated with reductions in beetle abundance, species richness, and diversity. In addition to affecting population dynamics, several developmental and physiological parameters—including larval growth, body size, muscle mass, and lipid reserves—are significantly impaired. Such alterations may ultimately reduce the ecological contributions of beetles to decomposition, nutrient cycling, and biological regulation of pest populations.

Overall, the available evidence indicates that pesticide contamination exerts substantial adverse effects on soil micro arthropods by impairing their survival, behavior, physiological functions, reproduction, and community structure. Because these organisms play indispensable roles in maintaining soil fertility and ecosystem stability, their decline may have far-reaching consequences for soil health and agricultural sustainability [63 - 66].

Effects of Pesticides on Soil Macro arthropods

Soil macro arthropods are indispensable components of terrestrial ecosystems, contributing to decomposition, nutrient cycling, soil formation, and the biological regulation of pest populations. However, these organisms are highly vulnerable to pesticide exposure, which may adversely affect their survival, reproductive success, behaviour, and ecological functions [67 - 69].

Collembola (Springtails)

Springtails (Order: Collembola) are among the most abundant soil arthropods and serve as valuable bio indicators of soil quality due to their high sensitivity to environmental pollutants. Numerous studies have demonstrated that pesticide exposure adversely affects their survival, reproductive capacity, and behavioural responses (70, 71). Dimethoate and chlorpyrifos significantly reduced the survival of collembolan populations. Similarly, exposure to ethoprophos completely inhibited reproduction in Folsomia candida (Willem). Behavioural studies further revealed that atrazine and the glyphosate formulation Zapp Qi 620 induced pronounced avoidance behaviour in springtails. In addition, chlorpyrifos markedly reduced springtail species richness, indicating that pesticide application can substantially alter community composition and biodiversity [72 - 76].

Acari (Mites)

Mites (Subclass: Acari) constitute another ecologically important group of soil arthropods that actively participate in decomposition, nutrient turnover, and regulation of soil microbial populations. Several investigations have demonstrated that pesticide contamination adversely influences both their behaviour and population density (77). Soil treated with chlorpyrifos, dimethoate, deltamethrin, copper, and spinosad was consistently avoided by mite populations. Furthermore, dimethoate significantly inhibited the growth of Hypoaspis aculeifer (Canestrini). Although the degree of susceptibility varied among mite species, pesticide exposure generally resulted in a significant decline in their abundance, suggesting detrimental effects on soil ecosystem functioning [78 - 80].

Formicidae (Ants)

Ants (Family: Formicidae) are considered ecosystem engineers because of their contributions to soil turnover, aeration, nutrient redistribution, and the natural suppression of insect pests. Several insecticides have been reported to negatively affect ant populations and their ecological activities. Chlorpyrifos significantly reduced ant abundance, while diazinon also caused marked declines in ant populations. Similarly, fipronil substantially decreased ant abundance. Exposure to a pesticide mixture containing glyphosate, clothianidin, and bifenthrin significantly reduced the predatory efficiency of ants against black cutworm eggs. In addition, bifenthrin impaired the mound-building behaviour of Lasius neoniger (Emery) and Solenopsis molesta (Say), thereby disrupting their normal ecological activities [81 - 83].

The documented declines in soil arthropod populations have significant implications for the ecosystem services that these organisms provide. Reduced abundance and diversity of decomposers such as millipedes, isopods, and springtails may slow the rate of organic matter decomposition, leading to the accumulation of plant litter and reduced nutrient availability for plants. This could, in turn, reduce agricultural productivity and increase dependence on synthetic fertilisers. The decline of predatory arthropods such as ants and beetles may disrupt biological pest regulation, potentially increasing pest pressure and the need for further pesticide applications, creating a positive feedback loop of pesticide use and ecological degradation. Furthermore, the loss of burrowing and tunnelling activities of soil arthropods may compromise soil structure, reduce water infiltration, and increase erosion risk. The magnitude of these functional consequences depends on the extent of arthropod decline, the resilience of arthropod communities, and the compensatory capacity of other soil organisms. However, the available evidence suggests that pesticide-induced arthropod decline poses a significant threat to the long-term sustainability of agricultural ecosystems.

Ecological Significance

Collectively, the available evidence demonstrates that pesticide exposure adversely affects soil macro arthropods by reducing survival, reproduction, growth, behavioral performance, and species diversity. Because these organisms play fundamental roles in decomposition, nutrient cycling, soil structure development, and biological pest regulation, declines in their populations may compromise essential ecosystem services. Consequently, minimizing the adverse effects of pesticides on non-target soil macro arthropods is critical for maintaining soil biodiversity, ecological resilience, and sustainable agricultural production [84 - 86].

Ecological Roles of Soil Arthropods

Soil arthropods perform a wide range of ecological functions that are essential for maintaining soil fertility, ecosystem stability, and sustainable agricultural productivity. Their activities influence decomposition, nutrient dynamics, soil structure, and numerous biological processes that collectively support healthy soil ecosystems [84 - 86].

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1. Decomposition of Organic Matter

One of the primary ecological functions of soil arthropods is the decomposition of organic matter. Various groups, including mites, springtails, diplopods, isopods, acari, and the larvae of numerous insects, feed on decaying plant residues, leaf litter, dead animals, and other organic materials. Through fragmentation and mechanical breakdown of these substrates, they accelerate the decomposition process and facilitate the conversion of complex organic compounds into simpler forms that can be readily utilized by microorganisms and plants (87). Soil arthropods also maintain mutualistic associations with microorganisms inhabiting their digestive tract. These microbial symbionts produce enzymes capable of degrading recalcitrant compounds such as cellulose and lignin, thereby enhancing the decomposition of plant biomass and promoting nutrient recycling (88,89).

2. Nutrient Cycling

Soil arthropods play a crucial role in nutrient cycling by regulating the movement and transformation of nutrients between the biotic and abiotic components of soil ecosystems. Nutrient cycling is governed by interconnected biological, geological, and chemical processes operating through various biogeochemical cycles (90, 91). During feeding, burrowing, and decomposition activities, soil arthropods stimulate microbial activity and accelerate the mineralization of organic matter, thereby increasing nutrient availability for plants. In addition, micro arthropods contribute to improved soil porosity and aeration through the formation of macrospores, which facilitate water movement and gas exchange within the soil profile (92). Feeding by collembolans on soil fungi has also been shown to increase the release of essential nutrients, particularly calcium (Ca) and nitrogen (N), into the soil environment (93). This process is especially important in acidic forest ecosystems, where large quantities of nutrients remain immobilized within accumulated organic matter, thereby enhancing nutrient bioavailability and ecosystem productivity (94).

3. Soil Structure Modification

Soil arthropods contribute significantly to the development and maintenance of soil structure. Larger soil fauna actively participate in soil mixing, aggregation, and turnover through their continuous burrowing and tunneling activities. These processes improve soil texture, enhance aggregate stability, increase both total porosity and macro porosity, and promote efficient water infiltration and retention. Collectively, these modifications improve soil aeration, root penetration, and overall soil physical quality (95). The activities of soil arthropods, together with various abiotic physical and chemical processes, regulate soil fertility and help mitigate the adverse effects of soil degradation by maintaining favorable soil structure and ecosystem functioning (96).

Applications of Pesticides

Pesticides are extensively employed in agriculture, public health, and industry because of their effectiveness in controlling a wide range of harmful organisms. Their principal applications are summarized below (97).

1. Enhancement of Agricultural Productivity

The primary objective of pesticide application is to protect agricultural crops from insects, weeds, pathogens, and other pests that reduce crop yield and quality. By minimizing pest-induced losses, pesticides contribute significantly to increased agricultural productivity, improved crop quality, and enhanced food security (98).

2. Public Health Protection

Pesticides play a vital role in public health programmes by controlling vectors responsible for the transmission of infectious diseases. Insecticides are widely used to suppress mosquito populations that transmit malaria, dengue, chikungunya, and other vector-borne diseases, thereby reducing disease incidence and improving community health [99].

3. Protection of Stored Agricultural Products

During post-harvest storage, agricultural commodities are vulnerable to infestation by insects, rodents, and other storage pests. Pesticides are therefore applied to protect stored grains and food products from deterioration, minimize post-harvest losses, and maintain both the quality and safety of stored produce [100].

4. Industrial Applications

Pesticides are also employed in industrial and structural pest management to protect buildings, wooden structures, warehouses, and other infrastructure from termites and various structural pests. Their application helps prevent structural damage and prolongs the service life of construction materials [101].

Environmental and Biological Concerns

Although pesticides provide substantial benefits in agriculture, public health, and industry, their indiscriminate and excessive use has raised significant environmental and biological concerns. Pesticide residues may adversely affect non-target organisms, including soil arthropods, beneficial insects, plants, wildlife, aquatic organisms, and humans. Consequently, understanding their ecological impacts is essential for developing sustainable pest management strategies that balance effective pest control with environmental conservation [102,103].

Impact of Pesticides [100 - 102]

Although pesticides have substantially contributed to agricultural productivity and disease management, their indiscriminate and excessive use has resulted in widespread environmental contamination and adverse health consequences. The major environmental and human health impacts associated with pesticide exposure are discussed below.

I. Environmental Impacts (104,105)

1. Soil Contamination

Following application, many pesticides persist in the soil for extended periods owing to their chemical stability. The accumulation of pesticide residues adversely affects soil quality by disrupting microbial communities, suppressing beneficial soil microorganisms, and reducing overall soil fertility (105,106). In addition, pesticide contamination negatively impacts non-target soil organisms, including earthworms and other beneficial macro fauna, thereby impairing essential ecological processes such as organic matter decomposition, nutrient cycling, and soil structure formation.

2. Water Pollution

Agricultural runoff is one of the major pathways through which pesticide residues enter rivers, lakes, reservoirs, and groundwater systems. These contaminants degrade water quality and pose serious risks to aquatic organisms by affecting their survival, growth, reproduction, and physiological functions (107). Persistent pesticide pollution also threatens freshwater biodiversity and ecosystem stability.

3. Air Pollution

Pesticides may become airborne during or after application through spray drift, volatilization, or wind erosion. These airborne residues can be transported over considerable distances, contaminating surrounding vegetation, wildlife habitats, water bodies, and nearby human settlements. Consequently, non-target organisms and human populations may be exposed to pesticides even in areas where they have not been directly applied [102].

4. Loss of Biodiversity

The widespread use of pesticides contributes significantly to biodiversity loss by adversely affecting numerous non-target organisms. Beneficial insects such as bees and butterflies, insectivorous birds, aquatic invertebrates, and other wildlife are particularly vulnerable to pesticide exposure. Declines in these organisms can disrupt ecological interactions, reduce pollination services, and alter food webs, and ultimately compromise ecosystem stability and resilience [102].

II. Impact on Human Health (108,109)

Human exposure to pesticides may occur through occupational activities, contaminated food and water, inhalation of pesticide aerosols, or dermal contact. Depending on the duration and intensity of exposure, pesticides can produce both acute and chronic health effects.

1. Acute Health Effects

Short-term exposure to pesticides may result in immediate toxic manifestations, including headache, dizziness, nausea, vomiting, skin and eye irritation, respiratory distress, and neurological symptoms. In cases of severe poisoning, pesticide exposure may lead to convulsions, respiratory failure, or death [110,111].

2. Chronic Health Effects

Repeated or prolonged exposure to pesticides has been associated with numerous chronic diseases. Several pesticide compounds have been identified as carcinogenic, mutagenic, and neurotoxic agents, increasing the risk of various cancers and other long-term health disorders. In addition, certain pesticides function as endocrine-disrupting chemicals by interfering with hormonal regulation and normal physiological processes (108,109).

3. Reproductive and Developmental Toxicity

Endocrine-disrupting pesticides may adversely affect reproductive health by impairing fertility and reproductive function. Prenatal or early-life exposure has also been associated with congenital abnormalities, developmental disorders, impaired growth, and neurodevelopmental deficits in children. These findings highlight the importance of minimizing human exposure to hazardous pesticides through safer agricultural practices and effective regulatory measures [110 - 112].

Future pest management strategies

Future pest management strategies should prioritize environmentally sustainable approaches that minimize adverse effects on non-target organisms while maintaining effective pest control. The adoption of integrated pest management (IPM), biological control, precision pesticide application, and environmentally compatible bio pesticides can substantially reduce ecological risks associated with conventional pesticide use. Furthermore, continued research on pesticide–arthropod interactions, ecological risk assessment, and the development of safer pest control technologies will be critical for conserving biodiversity, protecting ecosystem functions, and ensuring sustainable agricultural production. Integrating these approaches into agricultural practices will help achieve a balance between crop protection, environmental conservation, and long-term food security [113,114].

CONCLUSIONS

Pesticides have become indispensable tools in modern agriculture and public health because of their effectiveness in controlling pests, weeds, and disease vectors. However, accumulating evidence indicates that their ecological impacts extend far beyond their intended target organisms. Both terrestrial and aquatic ecosystems experience significant alterations following pesticide application, affecting the diversity, abundance, behavior, and ecological functions of numerous non-target species, particularly soil arthropods. While insecticides and herbicides effectively suppress target pests, they may simultaneously promote population increases of herbivorous arthropods by reducing natural enemies such as predators and parasitoids. Consequently, some herbivorous species may attain pest status following pesticide application. The ecological consequences of pesticide use are largely mediated through complex species interactions rather than direct toxicity alone. Reduced predation, diminished parasitism, competitive release, and changes in habitat structure collectively influence the composition and functioning of biological communities. Therefore, evaluating only the direct toxic effects of pesticides provides an incomplete understanding of their environmental consequences. Comprehensive assessment of both direct and indirect ecological effects is essential for predicting long-term impacts on biodiversity and ecosystem services.

Several limitations of the evidence base should be acknowledged. First, many of the studies reviewed were conducted under laboratory or semi-field conditions, and the extrapolation of these findings to field conditions involves significant uncertainty. Laboratory studies often use higher pesticide concentrations and lack the complexity of field conditions, including the presence of multiple pesticide residues, varying environmental conditions, and the interactions among different taxa. Second, the studies reviewed vary considerably in their methodological quality, including differences in exposure duration, endpoints measured, and study design. Third, the studies focus predominantly on acute effects and short-term exposures, with fewer studies examining the chronic, sublethal, and long-term effects of pesticide exposure. Fourth, there is a geographic bias in the literature, with most studies conducted in temperate regions, and relatively few studies from tropical and subtropical regions where pesticide use is increasing rapidly. Fifth, the studies examine the effects of individual pesticides, whereas field conditions often involve mixtures of multiple pesticides that may have interactive effects. Future research should prioritise: (1) field studies that examine the effects of pesticide exposure under realistic conditions; (2) studies that examine the chronic, sublethal, and long-term effects of pesticide exposure; (3) studies from tropical and subtropical regions; (4) studies that examine the interactive effects of pesticide mixtures; and (5) studies that quantify the functional consequences of arthropod decline for ecosystem services.

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