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Ecotoxicological Effects of Pymetrozine and Cartap on Earthworm (*Pheretima posthuma*): Implications for Soil Health and Environmental Sustainability

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Abstract
Agricultural intensification has increased reliance on chemical pesticides, raising concerns about soil health and biodiversity. This review examines the ecotoxicological impacts of Pymetrozine and Cartap on *Pheretima posthuma*, a sentinel earthworm species critical for soil fertility. Pymetrozine, a triazine derivative, primarily disrupts feeding behavior through chordotonal mechanoreceptor inhibition, while Cartap, a nereistoxin analogue, exerts stronger neurotoxic effects via nicotinic acetylcholine receptor antagonism. Evidence shows both compounds induce oxidative stress, impair enzymatic activity, disrupt reproduction, and alter locomotion, leading to population declines and reduced soil bioturbation. Cartap demonstrates higher persistence and bioaccumulation, posing greater long-term ecological risks compared to Pymetrozine. Environmental variables such as temperature and soil composition further modulate toxicity. The findings underscore the cascading consequences of pesticide exposure on nutrient cycling, microbial diversity, and ecosystem resilience. This review highlights the urgent need for sustainable pest management strategies and regulatory frameworks to safeguard soil health and environmental sustainability.

Keywords: Ecotoxicology, pymetrozine, cartap, earthworm bio-indicators, soil health sustainability

1. Introduction

Agriculture has long been the foundation of food security and economic growth, particularly in countries like India where farming sustains a large proportion of the population. The agricultural intensification has become necessary to meet the demands of a rapidly growing population, and this has led to a heavy reliance on chemical pesticides to secure crop yields (Aktar *et al*., 2009) [1]. While these agrochemicals have proven effective in pest control, their indiscriminate use has raised serious concerns about soil degradation, biodiversity loss, and long term sustainability of agro-ecosystems (Hussain *et al*., 2009) [24]. The pesticide residues not only persist in soil but also disrupt ecological balance by affecting non target organisms such as earthworms, which are critical for soil health and fertility (Kumar *et al*., 2024) [26]. Globally billions of dollars are spent annually on pesticides, with insecticides forming a major share of this expenditure (PAN Germany, 2012) [44]. Among them, Pymetrozine, a pyridine azomethine compound effective against sap sucking insects and Cartap, a nereistoxin analogue used against lepidopteran larvae, are increasingly applied in modern farming systems (Li *et al*., 2011; Ray, 1991). However, their persistence in soil and potential to bio-accumulate pose risks to beneficial soil fauna. Multigenerational studies have shown that even low concentrations of insecticides can impair survival and reproduction in earthworms, underscoring the long-term ecological risks of pesticide reliance (Martin *et al*., 2024) [33]. These findings emphasize the urgent need for sustainable pest management strategies that minimize collateral damage to soil ecosystems (Elhamalawy *et al*., 2024) [16].
Earthworms, often described as ecosystem engineers play a pivotal role in maintaining soil structure, nutrient cycling, and organic matter decomposition (Pelosi *et al*., 2014) [50]. Their burrowing activity enhances aeration and water infiltration, while their feeding accelerates the breakdown of organic residues into nutrient rich vermicast (Gajalakshmi and Abbasi, 2002) [19]. The sensitivity to pollutants and their intimate interaction with soil, earthworms are widely recognized as reliable bio-indicators in eco-toxicological studies (OECD, 1984) [43].

Recent research confirms that pesticide exposure alters earthworm physiology, reproduction, gut microbial diversity and biochemical composition, ultimately threatening soil fertility and ecosystem resilience (Kumar *et al.*, 2024) [26]. Thus understanding the eco-toxicological effects of Pymetrozine and Cartap on *Pheretima posthuma* is crucial for evaluating soil health and guiding sustainable agricultural practices (Wang *et al.*, 2012) [72].

2. Biological Profile of *Pheretima posthuma*

Pheretima posthuma (Vaillant, 1868), currently classified as *Metaphire posthuma* (Sims & Easton, 1972), is one of the most common earthworm species in India and South Asia. Morphologically, it is a cylindrical, segmented annelid with a clitellum that facilitates reproduction. Its ecological role is significant: burrowing enhances soil aeration and water infiltration, while feeding accelerates organic matter decomposition, producing nutrient rich vermicast that supports microbial diversity and soil fertility. The DNA barcoding using mitochondrial Cytochrome C Oxidase-1 (COI) sequences has revealed intra species genetic variation across Indian states, with Ranchi populations showing differences from those in Uttar Pradesh and Punjab, yet high similarity with strains from Thailand and China (Srivastava *et al.*, 2024) [68]. These findings highlight its wide distribution and adaptability. Importantly, its physiology characterized by permeable skin and constant soil contact makes it highly vulnerable to pesticide residues, reinforcing its role as a sentinel species in eco-toxicological risk assessment (Springer Nature, 2023) [67]. The *P. posthuma* serves as both an ecological engineer and a bio-indicator, bridging soil health with environmental sustainability. Its biological profile underscores why it is central to studies on pesticide toxicity, including the effects of Pymetrozine and Cartap.

2.1 Morphological and physiological traits

Pheretima posthuma (*Metaphire posthuma*) exhibits distinct morphological and physiological traits that make it a valuable model in eco-toxicological studies. Morphologically, it is a cylindrical, segmented annelid belonging to the family Megascolecidae, with a clitellum that plays a central role in reproduction. Its body wall is thin and permeable, facilitating cutaneous respiration and direct absorption of substances from the surrounding soil. This structural adaptation, while essential for survival, also increases its vulnerability to pollutants and pesticide residues (Srivastava *et al.*, 2024) [68]. Physiologically, *P. posthuma* contributes significantly to soil health through burrowing, which enhances aeration and water infiltration, and through feeding, which accelerates organic matter decomposition into nutrient rich vermicast. Its digestive system hosts diverse microbial communities that aid in nutrient cycling and organic matter breakdown, linking earthworm activity directly to soil fertility (Springer Nature, 2023) [67]. Recent studies highlight that exposure to agrochemicals alters enzymatic activity, protein metabolism, and reproductive efficiency, confirming its role as a sentinel species in environmental monitoring (Kumar *et al.*, 2024) [26].

2.2 Ecological functions in soil fertility

Pheretima posthuma (*Metaphire posthuma*) plays a crucial role in maintaining soil fertility through its ecological functions. Its burrowing activity improves soil aeration and water infiltration, creating favorable conditions for plant root growth and microbial proliferation. By ingesting organic residues and mineral particles, the species accelerates decomposition processes and produces nutrient rich vermicast that enhances soil structure and nutrient availability (Singh *et al*., 2023) [64]. The digestive tract of *P. posthuma* hosts diverse microbial communities that contribute to nitrogen mineralization and phosphorus mobilization, linking earthworm activity directly to soil nutrient cycling (Sharma *et al.*, 2024) [59]. Recent studies also highlight its role in mitigating pesticide residues by stimulating microbial degradation, thereby reducing chemical persistence in soil ecosystems (Patel & Mehta, 2024) [48]. These ecological functions underscore why *P. posthuma* is considered a keystone species in agro-ecosystems and a reliable bio-indicator for assessing soil health under pesticide stress.

3. Chemical Characteristics of Pymetrozine and Cartap

Pymetrozine is a selective insecticide belonging to the triazine group, with the molecular formula $C_{10}H_{11}N_5O$ and a molecular weight of 217.23 g/mol. Its chemical structure includes a pyridinylmethyleneamino substituent, which is responsible for its unique biological activity. The compound acts on chordotonal mechanoreceptors in insects, leading to feeding inhibition in pests such as aphids and whiteflies (Ausborn *et al*., 2005) [2]. Physicochemically, pymetrozine is a crystalline solid with a melting point of approximately 234 °C, low lipophilicity (LogP -0.18), and limited solubility in organic solvents such as methanol and DMSO (Fuog *et al.*, 1998) [18]. Toxicological evaluations indicate that pymetrozine has low acute toxicity to mammals, birds, bees, and aquatic organisms, and it is not considered mutagenic (PubChem, 2026) [52]. Cartap, in contrast, is a nereistoxin analogue with the molecular formula $C_7H_{15}N_3O_2S_2$ and a molecular weight of 236.34 g/mol. It is typically found as a white crystalline solid, highly soluble in water, and moderately soluble in organic solvents. While stable under normal conditions, cartap undergoes hydrolysis in alkaline environments (WHO, 2009) [73]. Its mode of action involves inhibition of nicotinic acetylcholine receptors, resulting in paralysis and eventual death of target insects. Unlike pymetrozine, cartap demonstrates moderate toxicity to mammals and is highly toxic to aquatic organisms, raising environmental concerns regarding its application (ChemicalBook, 2026) [8].

3.1Structural composition and classification

Pymetrozine is a triazine-based insecticide with the molecular formula $C_{10}H_{11}N_5O$. Its structure is defined by a 1,2,4-triazin-3-one ring substituted with a pyridinyl methylene amino group, which confers its selective activity against sap-feeding insects. This structural composition places pymetrozine within the chemical class of systemic insecticides that act as anti feedants. Recent studies emphasize its classification as a selective modulator of insect sensory systems, particularly chordotonal mechanoreceptors, which disrupt feeding behavior without causing immediate mortality (Qin, 2026) [53]. Cartap is a nereistoxin analogue belonging to the thiocarbamate group, with the molecular formula $C_7H_{15}N_3O_2S_2$. Its structure contains thiocarbamate functional groups that are critical for its neurotoxic activity. Cartap is classified as a systemic insecticide that interferes with nicotinic acetylcholine receptors, leading to paralysis in target pests. Modern toxicological assessments highlight its classification as a high-risk compound due to its strong water solubility and significant ecological impact, particularly on aquatic organisms (Zhang *et al*., 2023) [76]. The pymetrozine and cartap demonstrate distinct structural frameworks and classifications: pymetrozine as a triazine antifeedant with selective action, and cartap as a nereistoxin analogue with broad neurotoxic effects. Their structural differences directly influence their biological activity, environmental behavior, and safety profiles in agricultural use.

3.2 Mechanisms of insecticidal action

Pymetrozine is a systemic insecticide classified as a pyridine azomethine derivative. Its mechanism of action is unique compared to conventional neurotoxic insecticides. Instead of causing rapid knockdown, pymetrozine selectively targets chordotonal mechanoreceptors, which are sensory organs responsible for detecting movement and position in insects. By interfering with these receptors, pymetrozine disrupts the insect's ability to feed, leading to starvation rather than immediate death (Ausborn *et al*., 2005) [2]. Recent molecular studies confirm that pymetrozine acts as a TRPV channel modulator, further supporting its role in sensory inhibition rather than direct neurotoxicity (Yu-Xuan *et al*., 2023) [69]. Cartap is a nereistoxin analogue belonging to the thiocarbamate group. Its insecticidal activity is primarily due to its action on nicotinic acetylcholine receptors (nAChRs) in the insect central nervous system. Cartap functions as a non-competitive antagonist, blocking ion channels and preventing synaptic transmission. This results in paralysis and eventual death of the insect. Importantly, cartap is metabolically converted into nereistoxin, a more potent compound that enhances its neurotoxic effects (BenchChem, 2026) [5]. The dual pathway direct receptor antagonism and metabolic activation makes cartap highly effective against chewing and sucking pests but also raises concerns about its ecological toxicity.

Table 1: Comparative Ecotoxicological Profiles of Pymetrozine, Cartap and Other Agrochemicals

Parameter	Pymetrozine	Cartap	Other Agrochemicals	References
Chemical Class	Triazine derivative (pyridine azomethine)	Nereistoxin analogue (thiocarbamate group)	Organophosphates (acetylcholinesterase inhibitors); Neonicotinoids (nAChR agonists)	Ausborn *et al*., 2005; Ray, 1991 [2]
Molecular Formula / Weight	$C_{10}H_{11}N_5O$ / 217.23 g/mol	$C_7H_{15}N_3O_2S_2$ / 236.34 g/mol	Varies (e.g., Imidacloprid $C_9H_{10}ClN_5O_2$)	Fuog *et al*., 1998; WHO, 2009 [18, 73]
Mode of Action	Feeding inhibition via chordotonal mechanoreceptors	Blocks nicotinic acetylcholine receptors → paralysis	Organophosphates: inhibit acetylcholinesterase; Neonicotinoids: overstimulate nAChRs	Yu-Xuan *et al*., 2023; BenchChem, 2026 [5, 69]
Persistence in Soil	Moderate; weeks-months; microbial degradation	Higher persistence; hydrolyzes to nereistoxin	Organophosphates: moderate persistence; Neonicotinoids: high persistence, groundwater contamination	Qin, 2026; Zhang *et al*., 2023 [53, 76]
Bioaccumulation Potential	Low (LogP -0.18, limited uptake)	Moderate; accumulates in aquatic organisms	Neonicotinoids: moderate bioaccumulation in bees/fish	PubChem, 2026; Zhang *et al*., 2023 [76]
Toxicity to Mammals	Low acute toxicity, not mutagenic	Moderate toxicity; neurotoxic metabolite increases risk	Organophosphates: high acute toxicity; Neonicotinoids: moderate	WHO, 2009; PubChem, 2026 [52, 73]
Toxicity to Aquatic Organisms	Low	High; strong ecological concern	Organophosphates: moderate; Neonicotinoids: high (bee colonies, aquatic insects)	ChemicalBook, 2026; Zhang *et al*., 2023 [8, 76]
Impact on Earthworm Physiology	Feeding inhibition → reduced energy assimilation	Neurotoxicity → impaired locomotion, tissue degeneration	Organophosphates: neuromuscular disruption; Neonicotinoids: reduced burrowing & feeding	Wang *et al*., 2021; Singh *et al*., 2022 [71, 36]
Oxidative Stress Response	Elevated ROS, altered SOD/CAT/GPx activity	Stronger ROS induction, neurotoxic stress	Similar oxidative stress biomarkers observed in organophosphates & neonicotinoids	Li *et al*., 2023; Kumar *et al*., 2021 [28]
Reproductive Effects	Reduced cocoon production due to energy limitation	Stronger reproductive tissue damage → lower hatchling viability	Organophosphates: reduced fertility; Neonicotinoids: impaired reproduction in soil fauna	Rani *et al*., 2021; Mehta *et al*., 2022 [55, 38]
Population-Level Impact	Moderate decline; sub-lethal effects accumulate	Severe long-term suppression; higher risk of collapse	Organophosphates: population decline; Neonicotinoids: colony collapse in pollinators	Patel *et al*., 2024; Sharma *et al*., 2022 [4, 36]
Soil Ecosystem Effects	Moderate disruption of nutrient cycling, microbial shifts	Stronger suppression of microbial diversity, soil aggregation loss	Organophosphates: microbial suppression; Neonicotinoids: reduced soil biodiversity	Ghosh *et al*., 2021; Oliveira *et al*., 2022 [14, 41]
Comparative Risk	Lower chronic toxicity but still disrupts soil fertility	Higher ecotoxicological risk due to persistence and conversion to nereistoxin	Organophosphates: high acute risk; Neonicotinoids: chronic ecological risk	Das *et al*., 2021; Mukherjee *et al*., 2022 [13, 37]

4. Exposure Pathways and Bioavailability

Pymetrozine enters the environment primarily through agricultural application, where its systemic properties allow uptake by plant tissues and subsequent ingestion by sap-feeding insects. The main exposure pathway for target organisms is oral ingestion via phloem feeding, while non-target exposure occurs through residues in soil, water, and food crops. Due to its relatively low lipophilicity (LogP -

0.18), pymetrozine demonstrates limited bioaccumulation potential in animal tissues. Its bioavailability is largely restricted to insects feeding directly on treated plants, with minimal absorption in mammals and birds. Recent studies confirm that pymetrozine residues in soil and water degrade moderately, reducing long-term environmental persistence (Qin, 2026) [53]. Cartap exhibits broader exposure pathways due to its high water solubility. It can contaminate irrigation water, runoff and aquatic ecosystems, leading to significant non-target exposure. In insects, cartap is absorbed via ingestion and contact, and once inside the organism, it undergoes metabolic conversion to nereistoxin, which enhances its neurotoxic potency. Its bioavailability is high in both terrestrial and aquatic environments, with rapid uptake by insects and considerable risk to aquatic organisms (Zhang *et al*., 2023) [76]. Unlike pymetrozine, cartap demonstrates moderate bioaccumulation in fish and other aquatic species, raising ecological concerns.

4.1Routes of pesticide entry into earthworm tissues

Earthworms are exposed to pesticides through multiple entry routes that determine their internal bioavailability and toxicological burden. The most prominent pathway is dermal absorption across the cuticle, as their moist epidermis facilitates diffusion of both hydrophilic and lipophilic compounds from contaminated soil and pours water. The oral ingestion of soil particles and organic matter represents a major route, since earthworms consume large amounts of soil containing pesticide residues bound to colloids or organic matter, which are subsequently absorbed through the gut epithelium. A further route involves respiratory uptake via cutaneous gas exchange, where dissolved pesticides in soil pore water diffuse into the circulatory system during respiration. Collectively, these pathways cutaneous absorption, ingestion, and respiratory diffusion govern the extent of pesticide bioavailability in earthworm tissues, with efficiency influenced by pesticide physicochemical properties such as solubility and lipophilicity, as well as soil conditions including pH, organic matter and moisture content (Wang *et al*., 2021; Zhang *et al*., 2022; Li *et al*., 2023) [71, 76].

4.2 Accumulation and persistence in soil environments

Pesticides such as pymetrozine and cartap exhibit distinct behaviors in soil environments, influencing their ecological impact and long-term persistence. Pymetrozine, due to its relatively low lipophilicity and moderate water solubility, tends to remain in the upper soil layers where it is subject to microbial degradation and leaching. Its persistence is generally limited, with half-lives ranging from weeks to a few months depending on soil pH, organic matter content, and moisture, which makes it less prone to long-term accumulation (Qin, 2026) [53]. The cartap demonstrates higher water solubility and stability under neutral conditions, allowing it to move readily through soil pore water and accumulate in deeper layers. Once in the soil, cartap can undergo hydrolysis to nereistoxin, a metabolite that is more toxic and environmentally stable, thereby extending its persistence in soil ecosystems (Zhang *et al*., 2023) [76]. The accumulation of cartap is particularly concerning in aquatic-adjacent soils, where runoff can lead to contamination of water bodies. The pymetrozine shows moderate persistence with limited bioaccumulation potential, whereas cartap exhibits greater environmental stability and accumulation risks, highlighting the need for careful management of its application in agricultural systems.

5. Physiological Stress Responses

Exposure to pesticides such as pymetrozine and cartap induces a range of physiological stress responses in non-target soil organisms, particularly earthworms. These responses are typically characterized by oxidative stress, where the overproduction of reactive oxygen species (ROS) disrupts cellular homeostasis. Elevated ROS levels lead to lipid peroxidation, protein oxidation, and DNA damage, triggering antioxidant defense mechanisms such as increased activity of enzymes including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) (Wang *et al*., 2021) [71]. In addition to oxidative stress, pesticide exposure can impair metabolic processes, reducing energy reserves in glycogen and lipids, and altering enzymatic activity in the digestive tract. Cartap, due to its conversion into nereistoxin, exerts stronger neurotoxic effects, resulting in disturbances in neurotransmission and muscle contraction, while pymetrozine primarily induces feeding inhibition-related stress. Prolonged exposure also activates stress-related gene expression, including heat shock proteins (HSPs), which serve as biomarkers of sub-lethal toxicity (Li *et al*., 2023). Collectively, these physiological stress responses reflect the organism's attempt to maintain homeostasis under chemical pressure, but persistent exposure often leads to reduced growth, reproduction, and survival, thereby affecting soil ecosystem health (Zhang *et al*., 2022) [77].

5.1Alterations in locomotion and feeding behavior

Exposure to pesticides such as pymetrozine and cartap induces significant behavioral changes in soil organisms, particularly earthworms. Locomotion is often impaired due to neurotoxic effects, where pesticides interfere with neuromuscular coordination, resulting in reduced burrowing activity, slower crawling speed, and abnormal movement patterns. These alterations compromise the earthworm's ability to aerate soil and recycle nutrients, thereby affecting soil health. Feeding behavior is also disrupted, with pymetrozine acting as a feeding inhibitor by targeting chordotonal mechanoreceptors, leading to reduced ingestion of organic matter. Cartap, metabolized into nereistoxin, exerts stronger neurotoxic effects by blocking nicotinic acetylcholine receptors, which not only paralyzes feeding muscles but also diminishes overall food intake. Prolonged exposure results in decreased consumption rates, altered gut enzyme activity, and reduced energy assimilation, ultimately impairing growth and reproduction. Such behavioral modifications serve as early biomarkers of pesticide stress, reflecting sub-lethal toxicity that can cascade into broader ecological consequences (Wang *et al*., 2021; Zhang *et al*., 2022; Li *et al*., 2023) [71, 76].

5.2 Cellular and tissue level disruptions

Exposure to pesticides such as pymetrozine and cartap induces profound cellular and tissue-level alterations in non-target soil organisms, particularly earthworms. At the cellular level, pesticide stress often triggers oxidative damage, leading to excessive production of reactive oxygen species (ROS) that disrupt mitochondrial function and impair ATP synthesis. This imbalance results in lipid peroxidation of cell membranes, protein denaturation and DNA fragmentation, ultimately compromising cell viability (Kumar *et al*., 2021) [28]. Tissue-level disruptions are evident in the epidermis, gut epithelium, and nephridia, where structural degeneration, vacuolization, and necrosis are commonly observed. Cartap, due to its conversion into nereistoxin, exerts stronger neurotoxic effects, causing degeneration of neural tissues and impaired synaptic transmission, while pymetrozine primarily affects digestive tissues by inhibiting feeding-related sensory pathways (Singh *et al*., 2022) [36]. Prolonged exposure also alters histopathological features, including thickening of intestinal walls, disruption of muscle fibers, and inflammatory responses in reproductive tissues, which collectively impair growth, reproduction, and survival. These cellular and tissue-level disruptions serve as critical biomarkers of pesticide toxicity, reflecting both acute and chronic impacts on soil ecosystem health (Patel *et al*., 2023) [46].

Table 2: Ecotoxicological Impacts and Regulatory Context of Pymetrozine, Cartap and Other Agrochemicals

Impact Level	Pymetrozine	Cartap	Other Agrochemicals	Thresholds/Regulation	References
Chemical Class	Triazine derivative (pyridine azomethine)	Nereistoxin analogue (thiocarbamate group)	Organophosphates (AChE inhibitors); Neonicotinoids (nAChR agonists)	Classified as systemic insecticides	Ausborn *et al*., 2005; Ray, 1991 [2]
Molecular Formula / Weight	$C_{10}H_{11}N_5O$ / 217.23 g/mol	$C_7H_{15}N_3O_2S_2$ / 236.34 g/mol	Varies (e.g., Imidacloprid $C_9H_{10}ClN_5O_2$)	WHO/FAO chemical safety guidelines	Fuog *et al*., 1998; WHO, 2009 [18, 73]
Mode of Action	Feeding inhibition via chordotonal mechanoreceptors	Blocks nicotinic acetylcholine receptors → paralysis	Organophosphates: inhibit AChE; Neonicotinoids: overstimulate nAChRs	FAO recommends sub-lethal endpoints	Yu-Xuan *et al*., 2023; BenchChem, 2026 [5, 69]
Persistence in Soil	Moderate; weeks-months; microbial degradation	Higher persistence; hydrolyzes to nereistoxin	Organophosphates: moderate; Neonicotinoids: high persistence	NOEC/PNEC values regulate safe use	Qin, 2026; Zhang *et al*., 2023 [53, 76]
Bioaccumulation Potential	Low (LogP -0.18, limited uptake)	Moderate; accumulates in aquatic organisms	Neonicotinoids: moderate bioaccumulation in bees/fish	EU restrictions on neonicotinoids	PubChem, 2026; ChemicalBook, 2026 [52, 8]
Toxicity to Mammals	Low acute toxicity, not mutagenic	Moderate toxicity; neurotoxic metabolite increases risk	Organophosphates: high acute toxicity; Neonicotinoids: moderate	WHO pesticide classification	WHO, 2009; PubChem, 2026 [52, 73]
Toxicity to Aquatic Organisms	Low	High; strong ecological concern	Organophosphates: moderate; Neonicotinoids: high (bee colonies, aquatic insects)	FAO aquatic toxicity thresholds	ChemicalBook, 2026; Zhang *et al*., 2023 [8, 76]
Physiological / Behavioral	Feeding inhibition → reduced energy assimilation	Impaired locomotion, paralysis, abnormal burrowing	Organophosphates: neuromuscular disruption; Neonicotinoids: reduced burrowing	OECD guidelines for behavioral endpoints	Wang *et al*., 2021; Singh *et al*., 2022 [71, 36]
Oxidative Stress Response	Elevated ROS, altered antioxidant enzymes (SOD, CAT, GPx)	Strong ROS induction, inhibition of detox enzymes (GST, P450)	Organophosphates: severe oxidative stress; Neonicotinoids: moderate	Biomarker assays recommended	Li *et al*., 2023; Kumar *et al*., 2021 [28]
Reproductive Effects	Reduced cocoon production, lower hatchling viability	Severe reproductive tissue damage, embryonic mortality	Organophosphates: reduced fertility; Neonicotinoids: impaired reproduction	PNEC values guide reproductive safety	Rani *et al*., 2021; Mehta *et al*., 2022 [55, 38]
Population Dynamics	Moderate decline, sub-lethal effects accumulate	Long-term suppression, risk of collapse	Organophosphates: population decline; Neonicotinoids: colony collapse in pollinators	EU bans on neonicotinoids reflect risk	Patel *et al*., 2024; Sharma *et al*., 2022 [4, 36]
Soil Ecosystem Effects	Moderate disruption of nutrient cycling, microbial shifts	Strong suppression of microbial diversity, soil aggregation loss	Organophosphates: microbial suppression; Neonicotinoids: reduced soil biodiversity	FAO/WHO recommend IPM adoption	Ghosh *et al*., 2021; Oliveira *et al*., 2022 [14, 41]
Environmental Variables	Temperature increases feeding inhibition; weak sorption to organic matter	Temperature enhances conversion to nereistoxin; strong binding but bioavailable	Organophosphates: temperature-sensitive degradation; Neonicotinoids: persistent in sandy soils	Thresholds adjusted for soil type/climate	Hernández *et al*., 2021; Silva *et al*., 2022 [22]
Comparative Risk	Lower chronic toxicity but still disrupts soil fertility	Higher ecotoxicological risk due to persistence and conversion to nereistoxin	Organophosphates: high acute risk; Neonicotinoids: chronic ecological risk	Regulatory agencies emphasize chronic sub-lethal effects	Das *et al*., 2021; Mukherjee *et al*., 2022 [13, 37]

6. Biochemical Perturbations

Pesticide exposure in soil organisms leads to pronounced biochemical perturbations, primarily manifested through oxidative stress and disruption of enzymatic homeostasis. Elevated levels of reactive oxygen species (ROS) trigger lipid peroxidation, protein oxidation, and DNA damage, while antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx) show altered activity as compensatory responses. Additionally, detoxification pathways involving glutathione-

S-transferase (GST) and cytochrome P450 enzymes are upregulated, reflecting metabolic stress. Prolonged exposure also disturbs energy metabolism, reducing glycogen and lipid reserves, and alters neurotransmitter regulation, particularly under cartap exposure due to its conversion into nereistoxin. The biochemical perturbations serve as sensitive biomarkers of pesticide-induced toxicity, indicating both acute and chronic impacts on soil ecosystem health (Kumar *et al*., 2021; Singh *et al*., 2022; Patel *et al*., 2023) [28, 36, 46].

6.1 Protein Denaturation and Enzymatic Inhibition

Pesticide exposure often results in protein denaturation, where structural integrity of cellular proteins is compromised due to oxidative stress and direct chemical interactions. This leads to loss of enzymatic activity, misfolding, and aggregation, impairing essential physiological functions. Enzymatic inhibition is particularly evident in antioxidant systems, with reduced activity of superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), thereby weakening cellular defenses against reactive oxygen species. Detoxification enzymes such as glutathione-S-transferase (GST) and cytochrome P450 are also inhibited or dysregulated, reflecting metabolic stress and impaired xenobiotic clearance (Rani *et al*., 2021; Mehta *et al*., 2022; Choudhary *et al*., 2023) [55, 38, 12].

6.2 Shifts in Carbohydrate and Lipid Metabolism

Pesticides induce marked shifts in carbohydrate and lipid metabolism, disrupting energy homeostasis in soil organisms. Carbohydrate metabolism is affected through depletion of glycogen reserves and altered glucose utilization, reducing available energy for growth and reproduction. Lipid metabolism is similarly perturbed, with increased lipid peroxidation due to oxidative stress and reduced synthesis of essential fatty acids, impairing membrane integrity and energy storage. These metabolic shifts reflect adaptive responses to chemical stress but ultimately compromise organismal fitness under prolonged exposure (Kumar *et al*., 2021; Sharma *et al*., 2022; Patel *et al*., 2024) [4, 36, 28].

7. Reproductive Consequences

Exposure to pesticides such as pymetrozine and cartap has significant impacts on the reproductive physiology of soil organisms, particularly earthworms, which serve as key bioindicators of soil health.

7.1 Cocoon Production and Hatchling Viability

Pesticide stress often leads to a reduction in cocoon production, as reproductive tissues and associated hormonal pathways are disrupted. Oxidative stress and cellular damage impair gametogenesis, resulting in fewer viable cocoons. Hatchling viability is also compromised, with increased embryonic mortality and developmental abnormalities observed under prolonged exposure. Pymetrozine, due to its feeding inhibition mechanism, indirectly reduces reproductive output by limiting energy assimilation, while cartap exerts direct neurotoxic effects that impair reproductive tissue integrity. These changes collectively reduce reproductive success and serve as sensitive biomarkers of sub-lethal pesticide toxicity (Rani *et al*., 2021; Mehta *et al*., 2022; Choudhary *et al*., 2023) [55, 38, 12].

7.2 Long-Term Effects on Population Dynamics

Chronic pesticide exposure results in long-term consequences for population dynamics, including reduced recruitment rates, altered age structure, and population decline. Persistent reductions in cocoon production and hatchling survival translate into diminished population resilience, making earthworm communities more vulnerable to environmental stressors. Over time, these reproductive impairments lead to decreased soil bioturbation, nutrient cycling and ecosystem functioning. Cartap, with its higher persistence and bioavailability, poses greater risks for long-term population suppression compared to pymetrozine, which exhibits moderate environmental persistence. Such population-level disruptions highlight the ecological significance of reproductive toxicity in shaping soil biodiversity and sustainability (Kumar *et al*., 2021; Sharma *et al*., 2022; Patel *et al*., 2024) [4, 36, 28].

8. Influence of Environmental Variables

Environmental variables strongly influence pesticide toxicity and persistence in soil ecosystems. Temperature alters metabolic rates and chemical degradation, while soil composition and organic matter regulate adsorption, mobility, and long-term bioavailability.

8.1 Temperature Mediated Toxicity Variations

Temperature plays a critical role in modulating pesticide toxicity in soil organisms. Elevated temperatures accelerate metabolic rates, thereby increasing pesticide uptake and enhancing oxidative stress responses. This leads to greater enzymatic inhibition, faster depletion of energy reserves, and heightened mortality. Conversely, lower temperatures slow down metabolic activity, reducing pesticide bioavailability but prolonging persistence in soil, which can extend exposure duration. For compounds such as pymetrozine, higher temperatures intensify feeding inhibition effects, while cartap demonstrates stronger neurotoxicity under thermal stress due to enhanced conversion into nereistoxin (Huang *et al*., 2021; Silva *et al*., 2022) [21, 41].

8.2 Soil Composition and Organic Matter Interactions

Soil composition and organic matter significantly influence pesticide fate and bioavailability. High organic matter content enhances adsorption of pesticides, reducing immediate bioavailability but potentially prolonging persistence through slow release. Clay-rich soils tend to immobilize pesticides, whereas sandy soils facilitate leaching and groundwater contamination. For pymetrozine, weak sorption to organic matter results in moderate mobility, while cartap exhibits strong binding but remains bio-available due to its high solubility. These interactions determine exposure levels for soil organisms and shape long-term ecological risks (Martínez *et al*., 2021; Chen *et al*., 2023) [17, 11].

9. Soil Ecosystem Ramifications

Pesticide contamination in soils leads to a measurable decline in nutrient cycling efficiency, as earthworm activity and microbial-driven mineralization are suppressed. Simultaneously, microbial diversity and soil structure are altered, with beneficial taxa reduced and aggregation weakened, ultimately compromising long-term ecosystem resilience.

9.1 Declines in Nutrient Cycling Efficiency
Pesticide exposure disrupts earthworm activity and microbial processes, leading to a measurable decline in nutrient cycling efficiency. Reduced burrowing and feeding behavior limit organic matter decomposition, while oxidative stress impairs enzymatic activity essential for nitrogen and carbon turnover. Consequently, soils exhibit slower mineralization rates and diminished fertility, undermining ecosystem productivity (Fernández *et al*., 2021; Oliveira *et al*., 2022) [17, 41].

9.2 Impacts on Microbial Diversity and Soil Structure
Soil microbial communities are highly sensitive to pesticide residues, with exposure causing shifts in diversity, abundance and functional composition. Beneficial microbes involved in nutrient cycling are suppressed, while opportunistic or resistant strains proliferate, altering ecological balance. Structural impacts include reduced soil aggregation and porosity due to impaired earthworm bioturbation and microbial exudate production. These changes compromise soil resilience, water retention, and long-term sustainability (Ghosh *et al*., 2021; Li *et al*., 2023) [14].

10. Ecotoxicological Risk Evaluation
The ecotoxicological risk evaluation of pesticides such as pymetrozine and cartap requires integrating their persistence, bioavailability, and biological impacts on soil organisms and ecosystems. Pymetrozine, with moderate persistence and limited bioaccumulation, poses relatively lower long-term risks but still disrupts feeding behavior and reproductive success in non-target invertebrates. Cartap, however, demonstrates higher solubility, stronger bioavailability, and conversion into nereistoxin, amplifying its neurotoxic effects and ecological hazards. Both compounds impair earthworm physiology, microbial diversity and nutrient cycling, leading to cascading consequences for soil fertility and ecosystem resilience. Risk evaluation thus emphasizes not only acute toxicity but also chronic sub-lethal effects, ecological interactions, and potential for long-term population declines, underscoring the need for regulated application and monitoring in agricultural systems (Das *et al*., 2021; Mukherjee *et al*., 2022; Prasad *et al*., 2023; Banerjee *et al*., 2024) [36, 13, 51].

10.1 Threshold Levels for Safe Pesticide Application
Safe threshold levels for pesticide application are determined by ecotoxicological benchmarks such as No Observed Effect Concentration (NOEC) and Predicted No Effect Concentration (PNEC), which account for soil organism sensitivity, degradation rates, and bioavailability. For compounds like pymetrozine, moderate persistence requires careful regulation to avoid sub-lethal effects on earthworms, while cartap demands stricter limits due to its conversion into nereistoxin and higher aquatic toxicity (Hernández *et al*., 2021; Silva *et al*., 2022) [22, 41].

10.2 Comparative Toxicity with Other Agrochemicals
While compared with other agrochemicals, pymetrozine generally exhibits lower chronic toxicity due to its selective feeding inhibition mechanism, whereas cartap shows higher ecotoxicological risk because of its neurotoxic metabolite. Relative to organophosphates and neonicotinoids, cartap demonstrates comparable or greater impacts on soil invertebrates, while pymetrozine is less disruptive but still impairs reproduction and nutrient cycling. Such comparative evaluations highlight the importance of integrating pesticide-specific properties with broader agrochemical risk profiles to guide sustainable agricultural practices (Martínez *et al*., 2022; Chen *et al*., 2023) [35, 10].

11. Strategies for Sustainable Agriculture
Sustainable agriculture emphasizes minimizing pesticide risks while preserving soil health and ecosystem resilience. Approaches such as integrated pest management, precision farming, and the use of biopesticides reduce chemical dependence, while organic amendments enhance microbial diversity and nutrient cycling. Coupled with regulatory monitoring, these strategies balance productivity with ecological safety, ensuring long-term agricultural sustainability.

11.1 Integration of Organic Farming Practices
The integration of organic farming practices is a cornerstone of sustainable agriculture, as it reduces dependence on synthetic inputs while enhancing soil fertility, biodiversity, and resilience. Recent studies demonstrate that organic systems improve soil organic matter, promote beneficial microbial communities, and contribute to climate change mitigation through carbon sequestration (Meshram *et al*., 2026) [40]. Practices such as crop rotation, compost application, and biological pest control not only sustain productivity but also safeguard ecological integrity (Bharathi *et al*., 2025) [7].

11.2 Policy Frameworks and Farmer Awareness
Strong policy frameworks and farmer awareness initiatives are essential to mainstream sustainable practices. The EU Green Deal, for instance, sets ambitious targets to expand organic farming, while India's Zero Budget Natural Farming (ZBNF) promotes low-input ecological agriculture (Paul, 2026) [49]. Farmer training, extension services, and participatory guarantee systems enhance adoption by improving knowledge, market access, and compliance with certification standards. Institutional reforms that integrate biodiversity conservation and climate adaptation further strengthen the sustainability of agricultural systems (IUCN, 2026) [25].

12. Conclusion
The consolidates evidence that pesticides such as pymetrozine and cartap exert profound ecotoxicological effects on soil ecosystems. At the biochemical level, they induce protein denaturation, enzymatic inhibition, and metabolic disruptions, while at the reproductive level, they reduce cocoon production and hatchling viability, ultimately destabilizing population dynamics. Soil ecosystem functions are further compromised through impaired nutrient cycling, reduced microbial diversity, and weakened soil structure. Environmental variables such as temperature and organic matter content modulate these toxicities, highlighting the complexity of risk evaluation. The synthesis underscores that cartap poses higher ecological risks due to its neurotoxic metabolite, whereas pymetrozine, though less persistent, still exerts significant sub-lethal effects. Together, these findings emphasize the need for sustainable agricultural strategies, including organic farming integration, biopesticide adoption, and robust policy

frameworks to mitigate risks. Future research in soil ecotoxicology should prioritize long-term field studies, molecular biomarker development, and ecological modeling that integrates climate change scenarios. Strengthening farmer awareness and regulatory monitoring will be essential to balance productivity with ecological stewardship. Ultimately, advancing soil ecotoxicology provides a pathway to safeguard biodiversity, maintain soil fertility, and ensure the sustainability of agricultural systems in the face of chemical stressors.

CRediT authorship contribution statement

Ramandeep: Writing original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Komal: Editing, Anil Sharma and Komal Duhan: Visualization, Supervision and Editing,

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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