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Chemical pesticides and its effects: Monitoring towards a new concept in agroecosystem

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ABSTRACT

India depends heavily on agriculture as a means of ensuring food security. Even though agricultural productivity has increased significantly over the last few decades as a result of advances in irrigation technology, the persistence of agriculture continues to be challenged by insects, weeds, and pests while other factors continue to pose problems. Indispensable in agriculture, pesticides (including fungicides, insecticides, rodenticides, molluscides, nematicides, and herbicides) play an important role in reducing production problems and economic loss from agricultural production. While pesticide usage may provide significant benefits to agricultural practices, the long-term exposure to these inputs also has considerable potential for negative impacts on both the environment and the human population. Immediate and long-term impacts, such as neurological, patho-physiological, immuno-compromised or reproductive issues, will affect vulnerable individuals depending on the type and level of exposure to pesticides. In some cases, the ingestion of food exceeding permissible levels has resulted in severe consequences. Regular applications of certain persistent organochlorine compounds such as DDT, endosulfan, and glyphosate (in decreasing order) also have a damaging effect on soil microbiota and alter many of the nutrient cycling processes within terrestrial and aquatic ecosystems. Many developed countries have effectively banned the use of pesticides yet they continue to be heavily used in India. Therefore, it is very important to implement more sustainable and ecological methods of managing pesticide usage, as well as develop solutions that will minimize their residual and harmful effects, through the adoption of modern agricultural technologies.

KEY WORDS

Endosulfan; Environment; Glyphosate; Health; Pesticides

ARTICLE HISTORY

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Introduction

Agriculture is the most important sector in our country and forms the backbone of Indian economy. It includes cultivation of crops, rearing of livestock, agro-processing, fishing and forestry. Directly or indirectly, the farm sector employs as much as 70% of the Indian population [1]. The need for farm products has increased with the rise in population, meaning that the agriculture sector requires special attention to generate growth, employment, and economic prosperity. In the midst of an agrarian change, sustainable agriculture has emerged as a critical goal to achieve in the recent years. But pesticides are still being applied in the crop fields to boost productivity.

Pesticides are chemical substances that are used to repel, control or kill pests, thereby preventing diseases that are harmful to cultivated plants and crops. As their mode of action is not species specific, they also pose health risk to humans. Agricultural workers who come into contact with pesticides have rashes, blisters, skin irritation, sore throat, headache, and other symptoms. Prevalent chronic diseases include cancer and tumors, brain and nervous system damage, birth defects, and damage to lungs, liver, and other body organs. Pesticide exposure has also been linked to Parkinson's disease, asthma, depression, attention deficit hyperactivity disorder (ADHD), amyotrophic lateral sclerosis (ALS), and non-Hodgkin's lymphoma [2,3]. Furthermore, it is also linked to permanent neurodevelopmental disorders in infants and young children as their developing organs are more susceptible to the toxic effects of pesticides than adults [4]. As a result of pesticides' negative impacts, we need a regular pesticide residue monitoring programme to preserve the environment, biota, and human and animal health.

The chemical burden on natural ecosystems has increased as the agricultural sector has become more industrialized [5]. Pesticides also have adverse effects on terrestrial and aquatic animals, birds and the environment. Pesticides pollute the environment by contaminating surface and ground water, and causing air, water and soil pollution. Many non-target organisms like earthworm, detritus, fish, snail and other aquatic animals are prone to the ill effects of pesticides [6]. Hence, we need a regular pesticide residue monitoring programme to preserve the environment, biota and human and animal health. As a result, an integrated farming system that aims for sustainability, increased soil fertility, and biological diversity while avoiding pesticide use is urgently needed.

An overview on pesticides

Pesticides are substances or mixture of substances, otherwise known as agrochemicals, which are used to control, kill, prevent and destroy the unwanted pests in agricultural lands, farms, crop fields, public health programs and urban green areas. These pests include insects, plant pathogens, nematodes, microbes, fungi or weeds. Pesticides also play a vital role in crop protection, preservation of food, and

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prevention of vector-borne diseases. Pesticides are either natural toxins or synthetically derived compounds [7]. Earlier salt, sulphurous rock, extracts of tobacco, red pepper and chrysthanmus were used as pesticides [8]. In the 1940s, petroleum oil, heavy metals, arsenic were used to control weeds and unwanted pathogens. Then, they were replaced by synthetic pesticides like DDT (dichloro-diphenyl-trichloroethane) which soon became ubiquitous in the environment [9]. Pesticides can be found in various formulations like liquid, granules, gel, paste, pellets, powder, chalk, baits, etc. and are made available in different containers like glass, plastic or metal flasks, bottles, drums, traps, paper bags or plastic bags. On the basis of the pest they control, pesticides are classified into various types: Bactericides, Desiccants, Fungicides, Herbicides, Insecticides, Mammal repellent, Molluscicides, Nematicides, Ovicides, Piscicides, Rodenticides, Silvicides, Termiticides and several others [10]. Insecticides, herbicides and fungicides are reported to be most widely used in India. The following are the subtype of pesticides that protect the crop plants (Figure 1).

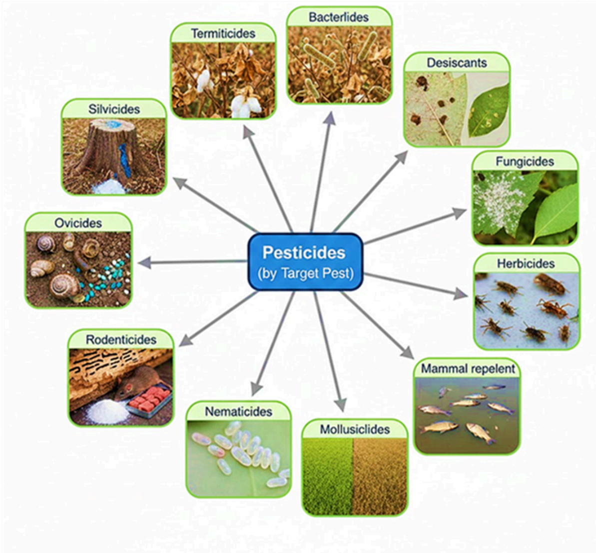

Figure 1. Pesticides classification on the basis of pest organism they control.

Insecticides

Insecticides are insect repellents targeted to kill or control the insect pests and insect vectors [11]. They are usually used in solid, liquid, granule or aerosol forms. Flying pests such as adult mosquitoes are attacked by aerosol sprays or fogs, whereas crawling insects are treated with surface powders, sprays or granules. Although the mode of action of insecticides is different, the toxic substances basically kill insects by getting inside their bodies via dermal, oral and respiratory entry [12,13]. Example; diethyltoluamide (DEET) and citronella (natural insect repellent).

Herbicides

Herbicides, also known as plant killers, are chemicals used to kill unwanted plants or weeds that take up the nutrients of desirable crops and result in their dormant growth. They kill the plants when they come in contact with them or when they are absorbed into the plant through leaves, stems, or roots. Examples of herbicides include paraquat, glyphosate 2,4-dichlorophenoxyacetic acid (2,4-D) and propanil [14]. The most widely used herbicide is "glyphosate," which is a broad-spectrum organophosphate pesticide closely related to current agriculture [5].

Fungicides

Fungicides are pesticides that control postharvest diseases and prevent the growth of fungi or fungal infections in plants. They manage important plant diseases which include leaf spot diseases, late blight, fruit rots, powdery mildews, rusts, and smuts. Fungicides also work as wood preservatives [15]. Examples of fungicides are Chloroneb, alkyldithiocarbamic acid, ferbam, and mancozeb [16]. The common classes of chemical pesticides are organochlorines, organophosphates, pyrethroids, carbamates, triazines and neonicotinoids. Based on the chemical composition, pesticides are of several types (Figure 2):

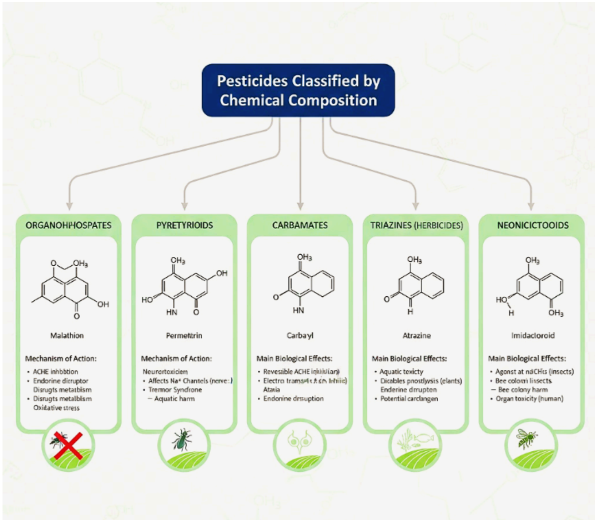

Figure 2. Types of pesticides on the basis of chemical composition.

Organophosphorus pesticides

Organophosphorus Pesticides (OPPs) are among the most widely used synthetic chemicals for the control of agricultural and domestic insect pests. They were promoted as an ecological alternative to organochlorines. OPPs include a variety of pesticides, the most common of which are glyphosate and chlorpyrifos. This class also includes pesticides such as malathion, parathion, and dimethoate which are known for their endocrine-disrupting potential [17]. OPPs affect the function of cholinesterase enzymes, decrease insulin secretion, disrupt normal cellular metabolism of proteins, carbohydrates and fats, and also cause adverse genotoxic effects. They also affect mitochondrial function, causing cellular oxidative stress and problems to the nervous and endocrine systems [5].

Pyrethroids

Pyrethroids are used as insecticides that work against insects belonging to the order Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera, Orthoptera and Thysanoptera [18]. The commonly used pyrethroids include alpha-cypermethrin, deltamethrin, and permethrin. Humans are exposed to Pyrethroids through skin contact and ingestion of food and water. Pyrethroids act on the sodium channels, change their conformation and cause Tremor type syndrome (T) whose symptoms include hypersensitivity, full body tremors, and

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ataxia. They also affect chloride channels, other ion channels and mitochondrial membranes of aquatic animals [19].

Carbamates

Carbamates (CMs), the esters of carbamic acid, are used as insecticides whereas its derivatives (dithiocarbamic acid and thiocarbamic acid) are used as herbicides [20]. CMs inhibit the activity of acetylcholinesterase (AChE) enzyme leading to an increase in neurotransmitter signalling. Overexposure to CMs may also cause various developmental and reproductive disorders including endocrine disruption, infertility, teratogenesis, and abortion [21].

Triazine herbicides

Triazines are persistent organic compounds that are used as broad-spectrum herbicides. The main triazine herbicides include amitrole (aminotriazole), atrazine, cyanazine, simazine and trietazine [22]. Atrazine is the most widely used herbicide which is applied in the form of water spray before the weed appears. Atrazine disables the electron transport chain, thus inhibiting photosynthesis of plants. Moreover, the water solubility of Triazine Herbicides makes it capable of leaching into ground and surface waters, causing harm to the aquatic ecosystem. Atrazine exposure is also linked to endocrine disruption, and potential carcinogenic or mutagenic effects in humans. Degradation of Atrazine compounds into less toxic products can occur through dealkylation and hydroxylation [23].

Neonicotinoids

Neonicotinoids are a new class of water-soluble neuroactive insecticides which include acetamiprid, clothianidin, dinotefuran, imidacloprid, and thiamethoxam. They are structurally similar to nicotine and act as agonists at the insect nAChRs (nicotinic acetylcholine receptors). Neonicotinoids cause a depolarizing blockade that leads to paralysis and later death in insects [24,25]. The persistence of Neonicotinoids in the environment negatively affects a range of non-target organisms including bees, butterflies and other invertebrates [26]. Imidacloprid is the most widely used class of insecticide in the world which is known to cause aspiration pneumonia, CNS effects, cardiovascular and respiratory failure in humans. Neonicotinoids induced toxic effects also include endocrine disruption, genotoxicity, hepatotoxicity, hyperglycemia, nephrotoxicity, and obesity (Table 1) [27].

Table 1. Classification of major chemical pesticides, their uses, and toxicological characteristics.

Pesticide class	Representative compounds	Primary agricultural use	Mode of action	Persistence	Major toxicological concerns
Organochlorines	DDT, Lindane, Aldrin	Insect control	Disruption of ion transport in neurons	Very high	Bioaccumulation, biomagnification, endocrine disruption, carcinogenicity
Organophosphates	Malathion, Parathion, Chlorpyrifos	Insect control	Acetylcholine sterase inhibition	Low–moderate	Acute neurotoxicity, chronic neurological disorders
Carbamates	Carbaryl, Aldicarb	Insect control	Acetylcholine sterase inhibition	Moderate	Neurotoxicity, reproductive toxicity
Neonicotinoids	Imidacloprid, Thiamethoxam	Systemic insect control	Nicotinic acetylcholine receptor agonism	Moderate	Pollinator decline, neurodevelopmental effects
Synthetic pyrethroids	Cypermethrin, Deltamethrin	Broad-spectrum insect control	Sodium channel modulation	Low–moderate	Aquatic toxicity, neurotoxicity
Herbicides	Glyphosate, Atrazine, Paraquat	Weed control	Photosynthesis and amino acid synthesis inhibition	Variable	Endocrine disruption, oxidative stress
Fungicides	Mancozeb, Chlorothalonil	Fungal disease control	Enzyme inhibition	Moderate	Thyroid toxicity, developmental effects

Effects of pesticides

Pesticides improve the standard of agro ecosystem and increase agricultural output by controlling pests, weeds and other vector-borne diseases. However, the long-term exposure and indiscriminate use of pesticides are toxic to humans, animals, and other non-target species. Pesticides also degrade the environment and biodiversity. Among all the categories of pesticides, insecticides are considered to be most toxic, whereas herbicides and fungicides are ranked second and third on the toxicity list respectively. Insecticides can either be natural or synthetic. The most commonly used insecticides include endosulfan, chlorpyrifos, carbofuran, triazophos, malathion, and diazinon.

Human health concerns associated with pesticide exposure

Lifelong exposure to pesticide is associated with various types of diseases in humans. So far, pesticides were used rampantly in order to improve the standard of agriculture and lives while

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its toxic effects remained largely unknown. Farmers, farm workers and pesticide applicators working on crop fields and farms are most vulnerable to the adverse effects of pesticides. Indirect exposure is also linked to various harmful effects on humans. Indirect effect is mostly seen in people who live in close proximity to the area exposed to pesticides. Several other factors responsible for exposure to pesticides include accidental spills, leakages, splashing or faulty spraying equipment. It also occurs when the applicators do not obey the basic safety guidelines written on the instruction manual and ignore wearing protective equipment and following sanitation practices such as washing hands and face after every spray operation [28].

Pesticides enter the human body through inhalation, ingestion and by contact with the skin. Upon entering the body, their residues are excreted, stored, or accumulated in the body fat. Pesticide residues detected in food items remain the major source of exposure, resulting in numerous negative health effects in adults. Furthermore, there are concerns regarding prenatal exposure and its consequences on children as pesticide residues have also been found in breast milk samples. The toxic effects of pesticides on human health depend upon several factors including – type of pesticide used and its concentration, duration and route of exposure, and health status of the exposed individual [5,29]. The effect can be either acute or chronic. Acute effects are immediate in nature and may appear within days whereas chronic or long-term effects are shown in individuals who are repeatedly exposed to low dose of pesticide residues over a long period of time ultimately resulting in irreversible damage and lethal clinical symptoms [30].

Acute or immediate effects of pesticide exposure are not severe and their symptoms include stinging of eyes, rashes, blisters, blindness, nausea, dizziness, diarrhoea, allergic sensitization, skin irritation, eye irritation, respiratory tract irritation, sore throat, cough, headache, vomiting, abdominal pain, extreme weakness, loss of consciousness etc.

Chronic or long-term effects of pesticides include neurological disorders such as memory loss, reduced visual activity and motor signalling. Moreover, it is also linked to immunological damage which causes allergies, asthma and hypersensitivity. The presence of pesticide is associated with cancer and several reproductive disorders like stillbirth, abortion and infertility. Long term exposure to pesticide may also damage the liver, lungs, and other body organs (Figure 3) [30].

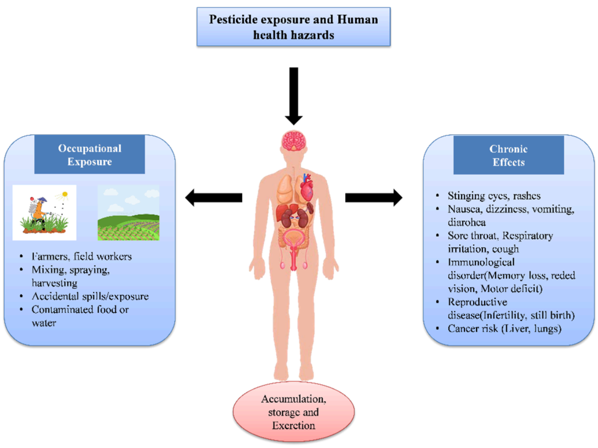

Figure 3. Pesticide exposure and associated human health hazards.

The widespread application of chemical pesticides has raised serious public health concerns due to both occupational and dietary exposure. Farmers and agricultural workers are directly exposed during pesticide mixing, spraying, and harvesting, often without adequate protective measures. Consumers are indirectly exposed through pesticide residues present in food grains, fruits, vegetables, and contaminated drinking water [31,32]. Chronic exposure to pesticide residues has been linked to a wide range of adverse health effects. Many synthetic pesticides act as endocrine-disrupting chemicals (EDCs), interfering with hormonal regulation and reproductive function. Neurotoxic effects, including cognitive impairment, memory loss, and developmental abnormalities, have been reported, particularly in children [33]. Long-term exposure has also been associated with increased risks of cancers, including leukemia, lymphoma, and breast cancer. The bio accumulative nature of certain pesticides further aggravates these risks by allowing toxins to persist and magnify through the food chain (Table 2) [34].

Table 2. Acute and chronic human health effects associated with chemical pesticide exposure.

Health System Affected	Observed Effects	Examples of Pesticide Classes	References
Nervous system	Neurotoxicity, tremors, memory loss	Organophos phates, carbamates	[35]
Endocrine system	Hormonal imbalance, infertility	Organochlorines, neonicotinoids	[36]
Reproductive system	Reduced fertility, birth defects	Pyrethroids, organophosphates	[37]
Immune system	Immunosuppression , hypersensitivity	Various broad-spectrum pesticides	[38]
Carcinogenic effects	Increased cancer risk	Organochlorines, glyphosate-based formulations	[39]

Effects of organochlorine pesticides

Organochlorine substances are mainly bioaccumulated in human tissues via the consumption of food. Moreover, in utero exposure to organochlorine can adversely affect the organogenesis and developmental stage of the foetus. DDT, endosulfan, and atrazine are some of the organochlorines that act as 'endocrine disruptor', which is defined by (U.S.) Environmental Protection Agency as "a chemical that interferes with the function of the endocrine system by mimicking a hormone, blocking the effects of a hormone, or by stimulating or inhibiting the production or transport of hormones." The majority of effects of organochlorines - female and male reproductive disorders and infertility, neurotoxicity, carcinogenicity, developmental toxicity, and immunotoxicity - are due to their ability to alter the levels of hormones, growth factors, enzymes and neurotransmitters. There are also concerns about potential tumorigenic and carcinogenic effects of organochlorine compounds [40].

Effects of pyrethroid insecticides

Pyrethroid insecticides work against a variety of pests by reacting with the voltage-gated sodium channels of insects and blocking the function of peripheral nervous system, resulting in

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paralyses. However, the overuse of pyrethroids has led to unintended consequences on human health [18]. Human exposure to pyrethroids may occur through skin, by inhalation and by food or water. Alpha-cypermethrin, deltamethrin, and permethrin, are the most commonly used pyrethroid compounds. Although there are no carcinogenic, embryotoxic, or mutagenic effects of Alpha-cypermethrin, they can cause reduced immunity in addition to affecting the central nervous system. Effects of deltamethrin on the human body include paresthesia, dizziness and headaches, lacrimation, abdominal pain, nausea, diarrhoea, vomiting, and hypersensitivity. Deltamethrin exposure also induces inflammation, nephrotoxicity, hepatotoxicity and is associated with alteration in foetal central nervous system and Parkinson's disease. Permethrin decreases the levels of anti-inflammatory IL-10 and is linked to allergies and asthma. Its exposure may lead to aggressive behaviour, agitation and symptoms such as vomiting, nausea, and respiratory distress. US EPA has classified Permethrin as likely to be carcinogenic to humans [19]. It is observed that there is a relationship between pesticides, Parkinson's and Alzheimer's disease [41]. Pesticide exposure can cause a range of neurological health effects such as loss of coordination and memory, reduced visual ability and reduced motor signalling [42].

Effects of endosulfan

Endosulfan is a toxic organochlorine pesticide used to improve productivity by controlling insect and arthropod pests [43]. Exposure of human body to Endosulfan is mainly through lungs, dermal contact, stomach and placenta [44]. Toxicity of endosulfan to different organ systems including nervous system [45], reproductive system, hepatic system, immune [46] and cardiovascular systems may lead to acute, subacute and chronic health effects in humans. Exposure of human umbilical vein endothelial cells (HUVECs) to endosulfan increases endothelial permeability by transcellular and paracellular pathways, thereby linking to cardiovascular diseases such as shock, cardiac function disorder, coronary arteriosclerosis and hypertensive disorder [47]. There are also concerns about potential relationship of endosulfan with leukemia as their exposure can induce DNA damage response via ATM-p53 mediated molecular mechanism in K562 cells [48].

Effects of organophosphates

Chlorpyrifos is one of the most widely used organophosphate insecticides. Acute exposure to organophosphates may cause headache, dizziness, numbness, tremor, nausea, sweating, blurred vision, respiratory depression, and slow heartbeat. Infants and young children are more susceptible than adults to the toxic effects of pesticides due to their underdeveloped organs, nervous system and immune system. Their high rates of cell division, immature organs, lower body weight and developing biological systems increase the risk of getting affected by pesticides. Exposure during early development period can also be fatal. Children's behaviour and physiology make them more likely to come in contact with greater pesticide effects than adults. Most pesticide exposure occurs through the skin as children have more skin surface for their size as compared to adults. Children also have higher respiratory rate, hence, the rate of inhalation of airborne pesticides is faster than adults. Their increased contact with floors, lawns, parks, pavements and playgrounds increase their exposure to pesticides [28]. In addition, chronic developmental and neurobehavioral disorders have also been linked to the exposure of chlorpyrifos [49].

Effect of pesticides on non-targeted species

The threat of using pesticide is not only restricted to humans. Many researches have been carried out to demonstrate how pesticides influence both terrestrial and aquatic creatures.

Effect on honeybees

Honeybees maintain ecosystem stability and food production by pollinating fruits, vegetables, and crops. Therefore, decline in bee populations has become a global concern. When honeybees (Apis mellifera) are exposed to the agricultural pesticide flupyradifuron (Sivanto), their survival reduces along with alteration in several immune and detoxification genes [50]. The exposure of nurse bees to individual or combined pesticides i.e., pyraclostrobin (fungicide) and fipronil (insecticide) reduces the expression of royal jelly proteins (MRJP1, MRJP2, MRJP4, and MRJP5) and impairs vital metabolic processes [51].

Effect on amphibians

For many years, organophosphorus (OP) insecticides have been among the most profoundly and ubiquitously used insecticides throughout the world. Although the toxicity of Chlorpyrifos has been studied extensively in animals but epidemiologically the data are limited. Measurable concentration of chlorpyrifos, endosulfan, malathion, diazinon and some other pesticides have been linked to the decline in amphibian population in California, USA [52]. Using Hyla regilla, it was found that depressed cholinesterase (ChE) activity is associated with reduced activity, uncoordinated swimming, and increased vulnerability to predators, depressed growth rates and greater mortality.

Effect on earthworms and microbial communities

The toxicity of two organophosphates pesticides chlorpyrifos and diazinon has also shown its effects on growth and reproduction of earthworm who are considered as farmers' friend. According to the available data, the less known Enchytraeid (Oligochaeta, annelid) earthworms play similar roles in agricultural soils but in a smaller scale. They are sensitive towards pesticides at different levels of biological organization, mainly in European agro-ecosystems [53]. The microbial aquatic ecosystems are regularly exposed to pesticides since they are commonly found within and around agricultural fields. The impacts of two herbicides (atrazine, glyphosate) and three insecticides (Malathion, carbaryl, and permethrin) on microbial communities in container aquatic habitats were studied using a microcosm technique. The findings suggested that individual pesticides or their mixtures can disrupt aquatic microbial populations, and that more research is needed to understand how these changes affect resident macroinvertebrate communities [54].

Effect on aquatic life

The effects of pesticides on aquatic ecosystems are typically studied using a hydrology transport model, which investigates chemical flow in water bodies. Chemicals that enter into water bodies through accidental spills, or uncontrolled washing of pesticides associated with treatment tanks are absorbed or ingested by aquatic life forms, causing organ failure in fishes and emergence of various diseases that eventually kills them. The chemicals also alter the pH of water body, hence interfering with the normal functioning of aquatic life.

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Pesticides and environment

Pesticides represent a serious environmental concern in addition to their possible harmful effects on human and animal health. Pesticides permeate the air, soil, water, and atmosphere. Water bodies get contaminated from mobile pesticides or from pesticide drift. Persistence of pesticides on land for prolonged periods of time decrease soil fertility, resulting in lower agricultural production rates. Air pollution occurs from volatile pesticides and remains in atmosphere in aerosol form [30]. Evidences suggest that crop products such as vegetables and fruits, contain trace amounts of pesticides that can harm organisms if consumed. Low quantities of Endosulfan and Chlorpyrifos contaminate surface and ground water, making it unfit for drinking.

Emergence of alternative pest management strategies

The growing awareness of the environmental and health risks associated with chemical pesticides has driven research toward alternative pest management strategies that are safer and ecologically compatible. These approaches aim to reduce dependency on synthetic chemicals while maintaining effective pest control and agricultural productivity. The emphasis is on sustainability, selectivity, and long-term ecosystem stability. Alternative strategies are designed to function within the natural regulatory mechanisms of agroecosystems. Rather than eradicating pests entirely, these approaches seek to maintain pest populations below economic threshold levels. Such methods include biological control, use of natural products, cultural practices, and advanced monitoring technologies [55,56].

Biopesticides as sustainable alternatives

Biopesticides are derived from natural organisms or their metabolites and represent one of the most promising alternatives to chemical pesticides. They are broadly categorized into microbial, botanical, and biochemical biopesticides. These agents are generally target-specific, biodegradable, and safer for non-target organisms. Microbial biopesticides such as Bacillus thuringiensis produce toxins that specifically affect insect gut physiology, while fungi like Beauveria bassiana infect and kill insect pests through natural pathogenic mechanisms (Table 3). Plant-derived compounds often act as repellents, antifeedants, or growth regulators [57,58].

Table 3. Types of biopesticides and their characteristics.

Type of Biopesticide	Source	Mode of Action	Target Pests	References
Microbial	Bacillus thuringiensis	Gut paralysis, cell lysis	Lepidopteran larvae	[59]
Fungal	Beauveria bassiana	Cuticle penetration, mycosis	Aphids, beetles	[60]
Botanical	Neem extracts	Antifeedant, growth inhibition	Wide range of insects	[61]
Biochemical	Pheromones	Disruption of mating behavior	Species-specific insects	[62]

Role of plant pesticides in agroecosystems

Plant pesticides occupy a central role in sustainable pest management due to their natural origin and multifunctional properties. These products are extracted from various plant parts such as leaves, seeds, bark, and roots and contain secondary metabolites like alkaloids, flavonoids, terpenoids, and phenolics [63]. Neem-based formulations are among the most extensively studied botanical pesticides. The active compound azadirachtin interferes with insect molting and reproduction, leading to population suppression without immediate toxicity [64]. Essential oils from plants such as eucalyptus, clove, and citronella exhibit strong insecticidal and repellent properties. Botanical pesticides degrade rapidly in the environment, reducing residue accumulation and minimizing ecological harm (Table 4) [65].

Table 4. Common botanical pesticides and their agroecosystem benefits.

Plant Source	Active Compounds	Pest Control Action	Advantages	References
Neem (*Azadirachta indica*)	Azadirachtin	Growth regulator, antifeedant	Low toxicity, biodegradable	[66]
Garlic (*Allium sativum*)	Allicin	Repellent, insecticidal	Broad-spectrum activity	[67]
Pyrethrum (*Chrysanthemum*)	Pyrethrins	Neurotoxic to insects	Rapid action, low residue	[68]
Eucalyptus	Essential oils	Repellent, fumigant	Environmentally safe	[69]

Integrated pest management (IPM)

Integrated pest management (IPM) is an effective, environmentally responsible method of managing multiple types of pest problems by using various control methods in a systematic manner. It involves monitoring and identifying pests, making decisions regarding pesticide use based upon action thresholds and using chemical pesticides as a last resort and only in a targeted manner. Other methods that are used in IPM include biological pest control, using resistant crops, crop rotation, intercropping, mechanical removal, and habitat manipulation. IPM will reduce the likelihood of developing pesticide resistance, reduce production costs and provide for greater biodiversity (Table 5). The use of IPM has been endorsed by the majority of international organizations such as FAO, UNEP, UNDP, IFA, and others as a key strategy for achieving sustainable agriculture [70].

Table 5. Components of integrated pest management.

IPM Component	Description	Role in Pest Control	References
Cultural control	Crop rotation, sanitation	Reduces pest habitat	[56] [71]
Biological control	Predators, parasitoids	Natural pest suppression	
Mechanical control	Traps, barriers	Physical removal of pests	[72]
Chemical control	Limited pesticide use	Emergency pest management	[73]
Monitoring	Pest surveillance	Informed decision-making	[74]

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Technological innovations supporting sustainable pest management

Technological advancements have significantly enhanced the effectiveness of alternative pest management strategies. Nanotechnology-based pesticide formulations improve solubility, stability, and targeted delivery, allowing reduced dosages and minimizing environmental exposure [75]. Precision agriculture tools, including GPS-guided sprayers, drones, and remote sensing, facilitate site-specific pesticide application. Ecological engineering approaches, such as creating flowering strips and refuges for beneficial insects, strengthen biological control mechanisms. Together, these technologies contribute to data-driven, environmentally responsible pest management systems [76].

International regulatory frameworks for chemical pesticide

International regulatory frameworks play a crucial role in managing the risks associated with chemical pesticides in agro ecosystems. The Stockholm Convention on Persistent Organic Pollutants (POPs) is a key international agreement aimed at eliminating or restricting the production and use of persistent organic chemicals globally [77]. This convention specifically targets many highly hazardous pesticides such as endosulfan, hexachlorocyclohexane isomers like lindane, chlordane, and hexachlorobenzene, all recognized for their severe environmental and health impacts [78-81]. The Convention, which was adopted in 2001 and entered into force in 2004, has a mechanism to add new compounds, and currently covers 28 POPs, significantly more than its initial listing [77]. Monitoring efforts, such as the Global Atmospheric Passive Sampling (GAPS) network, provide data on POP concentrations to inform the effectiveness of these chemical regulation efforts and highlight the continued presence and long-range transport potential of these substances [82].

Another significant framework is the Rotterdam Convention on the Prior Informed Consent (PIC) Procedure for Certain Hazardous Chemicals and Pesticides in International Trade. This convention provides a framework designed to empower countries to better manage the international trade of specific hazardous chemicals by requiring informed consent before their import [83]. However, the effectiveness of the Rotterdam Convention has been a subject of scrutiny, with research indicating continued large-scale and often illegal trade of listed chemicals. Weaknesses in its mechanisms and the permissiveness of export laws in high-income countries contribute to a disproportionate exposure to toxic substances in low- and middle-income countries, raising significant global health equity concerns [84].

Both the Stockholm and Rotterdam Conventions, alongside the Basel Convention (focused on controlling the trans-boundary movements of hazardous wastes), frequently encounter obstacles to effective implementation at the national level. These challenges often stem from issues such as weak coordination among national bodies, insufficient enforcement capabilities, and a lack of financial resources, particularly prevalent in developing countries [85]. Despite these difficulties, efforts are underway to enhance coordination and create synergies among these conventions through unified secretariats, aiming to improve overall governance and enforcement effectiveness [84,86].

National policies and recent amendments (2025/2026) in chemical pesticide management

Many countries are actively developing or revising their national legal frameworks to align with international agreements and enhance chemical safety. For example, some nations are focusing on updating hygienic standards for various chemicals, including those classified as Persistent Organic Pollutants (POPs), according to decisions from international conventions like the Stockholm Convention [87]. Some national policies are targeting specific issues, such as the regulation of contaminants in food, where updates are needed for permissible levels of pesticides in agricultural crops to harmonize with international safety standards [88]. Ukraine, for instance, is adapting its environmental policy, including climate change and potentially chemical management, to align with EU legislation, with legislative acts expected around 2025 [89].

The analysis of national policy amendments and guidelines from 2020 to 2026 reveals a significant focus on aligning national regulations with international standards and enhancing chemical safety. The year 2025 shows a notable increase in planned or expected policy updates. Common themes emerging from these initiatives include the development of maximum allowable concentrations (MACs) for hazardous chemicals like PFOA to address toxicity concerns and harmonize with international standards [90]. Furthermore, there is a strong emphasis on updating food safety regulations, particularly regarding permissible levels of pesticides in agricultural products, to ensure alignment with global norms and address the continued presence of hazardous chemicals identified by conventions such as the Rotterdam Convention [91].

The European Union's ambitious Green Deal aims for a toxic-free environment, influencing national policies of member states to cover the complete lifecycle of chemicals, including their design and remediation [92]. However, the precise definition of a 'toxic-free environment' is still evolving, and aligning risk assessment methodologies across different legislations remains a challenge [93]. For the years 2025 and 2026, planned updates in chemical monitoring guidance and reporting are emerging, particularly within the EU, with documents providing guidelines for reporting analytical results of food and feed samples for various chemicals, including pesticide residues [94]. These updates reflect on-going efforts to improve data quality and validation for chemical monitoring at both national and EU levels.

Discussion

Continual agriculture is central to providing food security in developing countries such as India that are faced with a growing population needing increased crop yield from sustainable and efficient means of cropping. Much of this has come from the increased production of crops made possible through the application of pesticides: i.e. insecticides, herbicides, fungicides, rodenticides, etc; however, this reliance on pesticides has also created a number of serious challenges to the sustainability in the long term, the ecological integrity of the environment, and the welfare of people.

As a result of the exhaustive and often indiscriminate use of pesticides, they have accumulated in soil, water, and living matter at a level that has altered the ecological balance of the environment. Persistent organic pollutants such as DDT and endosulfan have a number of serious ecological problems, given their long half-lives, their potential to bioaccumulate, and their ability to be biomagnified throughout the different trophic levels of the food chain. These compounds have also been shown to negatively affect soil microbes, with the result

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being a decline in the variety of microbes and a disturbance to many significant biochemical processes that occur within the soil, such as the ability to fix nitrogen and decompose organic matter. Likewise, herbicides, such as glyphosate, have also been shown to affect nutrient cycling and also alter water ecosystems as a result of their runoff or leaching into adjacent water bodies.

There are many different forms of pesticides and many different ways to use them causing both immediate and long-term health issues for humans and other non-target organisms. Immediate health issues include poisoning due to acute toxicity. Long-term exposure to pesticides has been linked to the development of neurological problems, endocrine disruption, immunotoxic properties, and reproductive dysfunction. Accumulating data indicates that long-term exposure (through residue) to pesticides may contribute to the development and progression of certain diseases including cancer, neurodegenerative diseases (e.g., Alzheimer), and developmental defects. The potential for harmful effects on public health raises significant concerns for agricultural communities where a large percentage of the population works with pesticides, and there is inadequate enforcement of existing regulations.

The continuing use of particular hazardous pesticides in India, in spite of restrictions on their use in many developed countries, is indicative of a significant deficiency in regulatory enforcement and a lack of public awareness related to hazardous pesticides and safer alternatives. Furthermore, poor management practices, excessive application, and failure to follow recommended safety procedures are all issues that compound the risks associated with pesticide use. Pesticide residues found in food products above permitted levels serve as motivation for increased monitoring and more rigorous quality control measures.

Conclusion

In order to move beyond the chemical pesticides, it is vital to develop sustainable and environmentally friendly farming techniques. There are a number of options available for reducing environmental impact while ensuring successful crop yields, such as Integrated Pest Management (IPM), biopesticides, organic farming, and precision agriculture. These include the potential use of new technologies (biotechnology and nanotechnology) that could help create more accurate pesticide application methods which would minimize negative consequences. In addition to regulatory frameworks, developing farmers' education, and implementing good farm management practices (i.e., surveillance systems) is necessary to reduce the negative impacts associated with pesticide use. Even though pesticides have played an important role in increasing agricultural productivity, their long-term harm to both the environment and human health cannot be neglected. A comprehensive approach that combines multiple technological advancements with environmental considerations is required to support sustainable farming practices while ensuring the long-term viability of ecosystems for future generations.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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