Frontiers in Health Informatics
ISSN-Online: 2676-7104
www.healthinformaticsjournal.com
2024; Vol 13: Issue 8
Open Access

The Impact of Agrochemicals on Human Health: A Global Perspective

Akansha Singh[1], Rupesh Kumar Pandey[2*], Lubhan Singh[3], Priyadarshini Soni[4]
[1]Research Scholar, Faculty of Pharmacy, Swami Vivekanand Subharti University, Meerut-250005
[*2,3,4] Faculty of Pharmacy, Swami Vivekanand Subharti University, Meerut-250005

Cite this paper as: Akansha Singh, Rupesh Kumar Pandey, Lubhan Singh, Priyadarshini Soni (2024). The Impact of Agrochemicals on Human Health: A Global Perspective. *Frontiers in Health Informatics, 13 (8) 743-756*

Abstract

Background

Pesticides are natural or synthetic substances developed to eliminate various types of pests. They are widely used in fields such as agriculture, forestry, aquaculture, and the food industry. However, their extensive use poses significant risks to public health and the environment, threatening both human well-being and ecosystems.

Main Body

The World Health Organization (WHO) classifies pesticides according to their harmful impacts, highlighting their significance in relation to public health. Their use can be reduced to a minimum by applying them sparingly and with a thorough understanding of their classification, which benefits both human health and the environment. This review addresses pesticides in terms of global perspectives, including their distribution around the world and their environmental effects. The primary literature has emphasized the potential uses of pesticides, their classification based on properties and toxicity, and their negative impacts on natural systems such as soil and aquatic environments. It also covers their effects on water, plant growth, metabolism, genotypic and phenotypic changes, impacts on plant defense mechanisms, and risks to human health, including genetic mutations, cancer, allergies, asthma, as well as their role in food preservation.

Short Conclusion

We have also outlined environmentally friendly pesticide management strategies as sustainable solutions, including bacterial degradation, mycoremediation, phytoremediation, and bioremediation using microalgae. Microorganisms utilize catabolic enzymes to break down pesticides and remove them from the environment. Pesticides are classified based on several criteria, such as their toxicity or hazardous effects, intended use or purpose, chemical composition, mode of action, timing of application, formulations, and source of origin. The World Health Organization (WHO) has classified pesticides based on their hazardous effects, emphasizing the importance of public health. By understanding these classifications, the excessive use of pesticides can be reduced through careful and judicious application, benefiting both public health and the ecosystem.

Keywords: Pesticides, Classification, Toxicity, Ecosystem

Introduction

Pesticides refer to substances used as weed killers, herbicides, rodent killers, aquatic pesticides, and nematodes [1]. They are usually recognized to serve a crucial impact in farmed development as they can reduce agricultural output wastage yet still boosting food yield as well as quality [2,3,4]. Poison production increased during World War II (1939-45) in response to the need to increase agricultural output and eradicate insect-borne illnesses. Furthermore, from the 1940s forward, the increased use of synthetic crop protection agents allowed for an increase in food output[1]. Furthermore, global usage of pesticides surged at an annual rate of about 11%, from 0.2 million tons in the 1950s to more than 5 million tons by 2000 [5]. Every year, three billion kilos of pesticide are used worldwide. [6], While just 1% of all insect repellent are efficiently employed to control insect pests on target plants[1]. The great majority of residual chemicals infiltrate or penetrate plants that are not the target and surroundings. As a result, pesticide infection has damaged the ecosystem and negatively impacted human health.

In accordance with the USA's Code of Federal Regulations (CFR), a chemical used in agriculture is any component or mixture of substances intended for use as a plant regulator, defoliant, or desiccant [7]. Pesticides are defined by the Food and Agriculture Organization, also known as the FAO, of the UN as any substance or mixture of substances used to control, avoid or eliminate any insect, animal, or human disease-causing vectors, undesirable plants, or animal species that affect food production, management, selling, storage, and transportation [8]. Pest management has used a wide range of chemical chemicals since antiquity. Sulfur compounds are well-known examples of insecticides that control insects and mites [9]. Pyrethrum, a plant (Chrysanthemum cinerariaefolium) derived pesticide has been used for over 2000 years. Salty water and chemical compounds (organic and inorganic) were commonly utilized to reduce pest populations until Paul Herman Muller introduced dichlorodiphenyl trichloroethane (DDT) as a strong pesticide in 1939 [10]. However, the usage of DDT helps to increase food yield and product shelf life. As a result, the global demand for DDT grew by the day, paving the way for the development of other insecticides. In 1975, the United States replaced DDT with organophosphates (OPs) and carbamates (CMs). [11]

Background and historical review of pesticide applications

Pesticides have been employed to protect agricultural crops since pre-2000 BC. The first known pest was atomic sulfur dusting, which was used in the ancient Sumer civilization approximately 4500 years ago in old Babylon. The Rig Veda, which is almost 4000 years old, makes mention to the use of poisonous plants for pest management [12]. To eliminate bugs in field crops in the 15th century, deadly compounds such as mercury, arsenic, and lead were introduced. In prehistoric Greece and Rome, inorganic chemicals like arsenic and sulfur were utilized to control bugs. The Chinese utilized arsenic as an insect repellant in the sixteenth century. In the 17th century, nicotine sulfate was manufactured from tobacco leaf residue and used as an exterminator. In the late 1800s, a toxic version of silver arsenate had been used to control the spread of the Denver bug in the United States of America. In the nineteenth century, two fresh chemical fertilizers, pyrethrum and rotenone, emerged that were considered more organically created from the flowers and tropical vegetation sources. Initial organomercury seedling covers emerged in German in 1913, yet chemical-based weed management was already utilized in French previously in the course of the twentieth century. [13]. The contemporary biochemical period for pests commenced in 1939, when the insecticidal characteristics of dichlorobiphenyl trichloroethane were discovered in the Swiss nation and organophosphorus repellent sprays originated in Germany. The first soil-acting carbamate herbicides were found in the UK in the year 1945 at the same period that the organochlorine insect apply chlorine was introduced in America and German soil.

Classification of Pesticide

They can be categorized according to multiple criteria, such as their level of toxicity, the types of pests they target, their intended function, chemical makeup, method of entry, mode of action, timing of application, different formulations, and historical usage.

Classification of pesticides on the basis of toxicity

It is mainly influenced by two key factors: dosage and exposure duration. Consequently, the quantity of the chemical (dose) and how often exposure occurs (time) result in two different types of toxicity: acute and chronic [14].

Acute Toxicity- Acute toxicity refers to the danger a pesticide poses to humans, animals, or plants after a single, short-term exposure. Even a small dose of a pesticide with high acute toxicity can be deadly. This type of toxicity can be categorized based on how it enters the body: through ingestion (oral), skin contact (cutaneous), or inhalation.

Chronic toxicity- Chronic toxicity refers to the harmful effects that develop from long-term pesticide exposure. This type of poisoning is a concern not only for those who handle pesticides directly but also for the general public, due to possible exposure through contaminated food, water, and air.

The World Health Organization (WHO) has focused solely on acute toxicity for pesticide classification. WHO categorizes pesticides into acute oral and acute dermal toxicity based on the estimated lethal dose (LD50) needed to kill half of the tested animals through ingestion or skin exposure. The current system, known as the "WHO recommended classification of pesticides by hazard," assigns pesticides to specific WHO hazard categories. In 2009, these classifications were aligned with the "Globally Harmonized System (GHS) Acute Toxicity Hazard Categories [15].

Categorization based on pest organisms killed and pesticide function (use).

Pesticides are classed according to the pest organisms they kill and their functions, as indicated in Table.[16,17]

Sl. No.	Type of pesticide	Target pests/Functions
1	Acaricides	Agents designed to eradicate or prohibit the emergence or formation of mites and insects.
2	Antifeedants	Chemicals that keep flies or other pests from feasting
3	Bird repellents	Chemicals that deter pigeons.
4	Chemosterillant	Chemicals that make a pest clean, prohibiting it from multiplying.
5	Desiccants	Act on plant by withering off their tissues.
6	Fungicides	Chemicals used to delay treat and elimination of fungus.
7	Herbicide softener	A compound that protects crops from herbicide damage without inhibiting the herbicide's ability to eliminate weeds.
8	Insect attractant	A chemical that attracts pests into traps, effectively removing them from crops, livestock, and stored goods.
9	Insecticides	A pesticide used to eliminate insects or interfere with their growth and development.
10	Larvicides	Prevent the growth of larvae.
11	Mammal repellent	A chemical that discourages mammals from approaching or feeding on crops and stored goods.
12	Molluscicides	Agents employed to eliminate slugs and snails.
13	Nematicides	Chemicals utilized for the management of nematodes.
14	Ovicides	Restrict the development of insect and mite eggs.
15	Piscicides	Functions as a deterrent to fish.

16	Rodenticides	Substances employed to exterminate rats and similar animals.
17	Termiticides	Eliminate termites.
18	Virucide	An agent capable of destroying or inactivating viruses.

Classification of Pesticides on the basis of Chemical Composition [18]

The most widely used and effective method for categorizing pesticides is by their chemical structure. Pesticides such as insect repellents, weed killers, chemical herbicides, and rodent killers are also classified based on their chemical compositions as follows:

Insecticides: Insecticides are classified chemically as Carbamates (Carbaryl), Organochlorine (Endosulfan), Organophosphorus (Monocrotophos), Pyrethroids (permethrin), Neonicotinoids (Imidacloprid), and miscellaneous pesticides such as Spinosyns (Spinosad), Benzolureas (diflubenzuron), Antibiotics (abamectin), among others.

Fungicides: Fungicides are classed as aliphatic nitrogen (dodine), amide (carpropamid), aromatic (chlorothalonil), dicarboximide (famoxadone), dinitrophenol (dinocap), and so on.

Herbicides-: The herbicides are anilide herbicides (flufenacet), phenoxyacetic herbicides (2, 4-D), quaternary ammonium herbicides (Paraquat), chlorotriazine herbicides (atrazine), sulfonylurea herbicides (chlorimuron) etc.

Rodenticides – They are categorized as inorganic rodenticides (Zinc phosphide, Aluminum Phosphide) and coumarin rodenticides (organic) (bromadiolone, coumatetralyl).

Classification of pesticides on the basis of Mode of Entry [19]

S. No.	Type of Pesticide	Description
1	Systemic Pesticides	These are toxins that get metabolized by wildlife or plants and transmit into unaffected tissue.
2	Stomach poisons	It penetrates the pest's body via its oral cavity and the gastrointestinal tract.
3	Contact pesticides	It works on the intended pests when they enter into sensation of touch.
4	Repellents	Repellents cannot eradicate parasites but are unpleasant adequate to repel them away from handled regions. They also hinder insects' capability to find food.

Taxonomy according to their mode of effect [20]

a) **Growth regulators-** Substances that impair the regulation of hormones and the production of protein, eventually lead plant life to perish. e.g. 2,4-D

b) **Amino acid synthesis regulators** – Chemicals that block an identified kinase that regulates amino acid biosynthesis. e.g. Glyphosate

c) **Lipid synthesis inhibitors** – It suppresses the generation of omega-3 fatty acids, which are necessary for the generation of lipids. e.g. Clodinafoppropargyl

d) **Seedling growth regulators-** It reduces proliferation of cells and triglyceride or protein production in plants. e.g. Butachlor

e) **Photosynthetic inhibitors** – blocks ion transport in photosynthetic and the utilization of sunlight into chemical power. e.g. Atrazine

f) **Cell membrane disrupters** – breaks the cellular barrier. e.g. Paraquat

g) **Pigment inhibitors-** inhibits the production of carotenoids required for metabolism. e.g. Clomazone

Pharmacological description based on the way and when it functions [21]

Contact Pesticides – These herbicides suppress insects according to the loop. The insects are eradicated by being attacked directly or crawling over objects infused with a persistent impact pesticide

Systemic pesticides Chemicals become absorbed by livestock or animal and transferred to unprotected organs or fungicides circulate through affected crops, killing certain bugs and pathogens.

Foliar Pesticides – These are put on to trees' stems, foliage, and limbs.

Soil applied Pesticides - These are sprayed to the ground. Many of these substances nutrients are picked into the bases and transmitted throughout the plant's life cycle.

Fumigants - Chemicals that are sprayed as a poisonous gas or as a hard substance or solution that produces a toxic vapor and enters infrastructural or ground fractures.

Pre-plant herbicides- These are administered to the land before sowing or replanting.

Human Pesticide Exposure and Risk Considerations

Human contact with poisons may happen through job exposure, such as for farmers who work in open spaces and greenhouses for cultivation, chemical sector personnel, and residential insect managers [22,23]. Whether or not the activity entails the application of herbicides, the availability of such compounds in the place of employment is a possible source of exposure during work. Professionals who combine, demand, shipping, and administer formulated toxins are firmly regarded as the group of individuals that gets the greatest amount of contamination due to the physical nature of their trade and are thus at the greatest risk of probable severe stupor [24]. exposition to pesticides can happen from unintended accidental chemical data loss or malfunctioning sprayed machinery. Personnel vulnerability rises when they do not follow spraying use instructions, particularly when they disregard fundamental security recommendations such as donning protective clothing and wiping the fingers after chemical handling or prior to dining. Multiple variables may impact susceptibility during neonicotinoid treatment [24]. The type of composition used in chemical goods may determine the degree of dose. Fluids are susceptible to overflowing and bursting, resulting in either direct or indirect cutaneous touch via garment infection. When particles are put into the use of devices, they can produce dirt, which may lead to contact with the cheeks and pupils, in addition to difficulty breathing. The containers of chemical products can additionally raise potential exposure. For example, with respect to the type of storage and the active ingredient design, removing herbicide sachets can result in a certain amount of toxicity. Also, the size of plastic bottles, cans, or other liquid vessels can affect the likelihood of tipping and spraying. In addition, supplementation materials employed in chemical mixtures that boost biological productivity (e.g., increase interaction among the substance that acts and its particular cellular goal) in addition to help with use and accomplish seek organisms may be hazardous, leading to the general impact when subjected to a business herbicide item [25]. The climate at the moment of utilization, including wind humidity and ambient temperature, could impact the molecular volatility of the product, the rate of sweat in the body of a person, and the use or unique protect gear by consumers [26]. Wind greatly enhances spritz dispersal and proximity to the operator. The proportion of poison wasted from the intended region and the length of time flown grow with the speed of the wind, consequently faster winds frequently result in greater wander.

Moreover, reduced atmospheric humidity combined with elevated heat cause droplets of spray to vanish quicker separating the spray nozzle and the intended item than greater relative humidity as well as low temperature. For example, Personnel' basic cleanliness when using pesticides can also have an enormous effect on exposure. Additionally, the rate and extent of pest dealing with, both periodically and across a lifetime, affect toxicity. Conversely, a single farmer who administers the chemical twice per year had less contact with it than an official sprayer who usually dispenses a poison for a few successive weeks or days in a given season.

The public at large usually gets subjected to pesticides through eating or drinking of chemical-contaminated foods and beverages, but significant pesticide exposure may happen while residing near a chemical-using worksite or if employees take polluted goods house [27,28]. The traces of pesticides in the environment, food, and tap water can appear in tiny quantities and over an extended amount of life.

Yet, meaningful links between particular chemical compounds and specific well-being can only be demonstrated in experimental studies, and the concentrations used in these investigations are considerably bigger than the lawfully imposed pest rules and regulations [29]. As a consequence, these examinations seem to present very small risks to human wellness. The actual amount of prolonged exposure, nevertheless, may be far greater than that envisaged due to certain nutritional habits, leftover deviations across single food groups, and the consumption of an identifiable food product just at a single visit [30] Individuals can be displayed during the preparation and application of pesticides or even after the procedures are completed, while retarded being subjected can occur through respiration of debris found on things, clothing, mattresses, meals, debris, tossed chemical cases, or usage tools. [Additionally, using insecticide around the home or lawn can lead to unintentional harm. The most common sources for contact include pesticide drips, inappropriate implementation, or inadequate storage as a result of using the chemical before studying or considering the warning label. Agricultural mismanagement, such as moving goods from their original packages into home containers, as well as a failure to follow label commands, can also be causes of exposure.

Humans Health Risks of Pesticide Exposure

Pesticides are toxic play a crucial part in the growth of agriculture; there is an immense dependence on pest therapies to meet the immense need for food supply from a growing populace. This causes stress in the environment and has a detrimental negative effect on individuals all over the world [31,32]. Employees creators, nozzles, blenders, loads, and farm workers are all at high risk for being directly in contact with toxins [33,34,35]. Interaction with dangerous substances and scenarios expands dramatically during assembly and composition since the procedures engaged are not without risk. Furthermore, people are physically contact with herbicides via the skin and inhale harms from the air. Industrial workers are also at a greater risk since they must handle several dangerous compounds, including insecticides that raw materials, hazardous solvents that are and inactive vehicles [36]. Humans are indirectly exposed to pesticides through polluted soil, water, the atmosphere, and the food system [37]. Persons can be susceptible to toxins in a variety of ways, whether directly or indirectly [38], which leads to a wide range of negative health effects.

Acute Toxic Effects

The ingestion of pest produces severe poisoning symptoms that may last from a few seconds to a few weeks [39]. Intoxication impacts both the periphery muscarinic and nicotinic receptors, as well as the brain [40,41] Indications of a dopaminergic panic include feeling sick, throwing up, stools, cramping in the abdomen, pee incontinence because miosis, spit, lacrimation, bronchorrhea, cardiac arrest, low blood pressure, fasciculation, limb weakness fainting, disorientation, a state of coma, and breathing problems [42]. The consequences may occur immediately after becoming exposed to chemicals [43] likewise, if serious issues are not treated correctly and promptly, mortality could happen.

[44] CPF's harmful impacts on histopathological changes in pseudo branchial nerve secretory cells (PNSCs) of a neuroendocrine system of the intestines region, the optic tectum (OT), and the cortex, as well as biologic alterations (acetylcholinesterase (AChE) action and anti-oxidant markers) in the cerebral cortex along with locomotory changes in behavior in air-breathing fish like catfish Enteropneusta's fossils. The research discovered that acute contact with CPF for only a brief amount of time can produce regulation of PNSC neurosecretory operation, changed brain metabolic activity, and diminished locomotory/swimming abilities in goldfish [45] Thmx's acute toxic effects on A. leptodactylous were studied utilizing a variety of biomarkers. Thmx had a 96-hour LC50 value of 8.95 mg/L as the active component. Thmx has very harmful effects on crayfish, hence they are endangered in places where this herbicide is until [46] We evaluated the appropriateness of a silent administering approach with a rubber the o-ring storage to analyze the impacts of PCP on Daphne's magnum. The study revealed that the coefficient of dispersion of PCP between ethanol and a test solution (log KMeOH:ISO) was 2.1, enabling for a constant dosage level during the entire study. Research on acute

toxicity with passively dosage and vehicle blasting showed EC50 readings of 576 and 485 µg/L for 24 h, and 362 and 374 µg/L for 48 h. These findings correspond with previous study [47] The acutely lethal effects of a one-hour pulsing rehabilitation using various chemical pesticides on mature and adolescent (<72 hrs old) crimson-spotted rainbowfish Melanotaenia duboulayi (Castlenau). The study found that temephos and pirimiphos-methyl were hazardous to juveniles, with 24-hour pulse exposure LC50 values of 27 and 15 ug/L, respectively. Pirimiphos-methyl was the more deadly of the two OPs, with a fatal dose ratio of 1.8 (95% CL 0.5–6.4). These pulse exposure LC50 values were 40 and 4.5% of the expected environmental concentrations (EECs) in a 15 cm deep water body, correspondingly.

Chronic Disease

A huge quantity of data acquired from laboratory animals support the potential of chronic health concerns associated with pesticide exposure [48]. However, epidemiological information is not available for all health conditions. Pesticides have been linked to a variety of chronic diseases and ailments [49], includes malignancies and bad reproductive consequences[50], male sterility [51], peripheral neuropathies [52], neurobehavioral disorders [53], decreased immunological function [54], and allergic sensitization reactions, notably those of the skin [55]. Furthermore, the majority of the herbicides tested harm male reproductive systems[56], causing sperm damage [57], DNA damage [58], and abnormal sperm morphology For instance, long-term, low-dose exposure to organophosphorus compounds causes cumulative inhalation of cholinesterase activity, which leads to chronic illnesses [59].

[60] Glyphosate's effects were examined at low concentrations; the decrease in Clustering mRNA levels revealed that glyphosate targeted Sertoli cell integrity. Glyphosate had a long-term effect on germ cells at 50 nm, 500 nm, and 5 µm, as evidenced by a decrease in their

[61] To examine claimed exposure to the Romford Mines/Landfill Hazardous Site in relation to long-term illnesses amongst residents of the Ramapough Lunaape Turtle Clan nation along with other inhabitants of Ringwood, Australia, New Jersey. The investigation's conclusions indicated significant links between Ringwood inhabitants of Native American origin and health issues, as well as self-declared likelihood of Epa sites contact. The investigation's conclusions indicated significant links between Ringwood inhabitants of Native American origin and health issues, as well as self-declared likelihood of Epa sites contact.

Pesticide and Neurotoxicity

Many pesticides, including organophosphates, organochlorines, and carbamates, have harmful effects on the central and peripheral nervous systems. Pesticides have acute or chronic, long-term or short-term effects on the neurological system due to high or low-level exposure throughout adulthood, childhood, or in utero exposure, and they can cause highly chronic nervous illnesses such as Parkinson's disease [62].

Alzheimer disease

Dementia is defined by an impairment of cerebral functioning; rates of it have risen in recent years A potential reason for the present spike can be attributed to a rise in exposure to pesticides, which may have worsened the cause of memory. Yet, certain research studies emphasize that poisons hinder brain function at the level of molecules by mistrusting tiny tubules and hyperphosphorylation, resulting in dementia [63] Organic phosphate and organochlorine insecticides have been found to disrupt acetylcholinesterase regulation at connections between neurons in the nervous system, perhaps leading to cognitive impairment, particularly in older persons [64]. Another study shows that several weeds (rotenone that and paraquat) which influence the bioenergetically functioning of cells with mitochondria, gas digestion, and antioxidant function, resulting in memory loss [65].

Parkinson disease

Parkinson's disease occurs when serotonin cannot be made by the substantial nig cell (dopamine-producing) in the nervous system, resulting in lack of cooperation, shaking, and diminished motor control. According to research, certain chemical pesticides, such as rotenone and paraguata, damage neurons that produce dopamine and inhibit dopamine production, resulting in Parkinson's disease [66]. Pesticide consumption has been linked to some cases of Parkinson's disease. Chemicals and their derivatives disrupt mtdna and alter exotic foods metabolism, resulting in Parkinson disease [67] In another investigation, it was revealed that treating rats to rotenone resulted in degeneration in the external nervous system as time passed, as well as a decrease in sensory nerve conduction speed, especially in the sciatica nerve. It is caused by a shortage of adrenaline and a malfunction of neuronal receptors in the area around the brain [68].

Organophosphate and neurotoxicity

According to study, insecticides (OP, carbamate, organochlorine) and fungicides behave as neurotoxins, modifying synaptic neurotransmission. Organophosphates (OPs) have been studied in detail, but critics argue that they produce two types of effects: immediate reactions lasting only seconds, which can include symptoms such as migraine attacks, vomiting, pupil constriction, collapse, excessive sweating, tearing, and muscle twitching. Life-threatening effects include reduced muscle tone, tremors, breathing difficulties, and fluctuations in blood pressure, which can result in seizures and lethargy. Exposure to organophosphates (OPs) can lead to a condition known as OP-induced delayed polyneuropathy, where the axonal component of the cell is severely damaged and unable to regenerate, due to the action of specific esterase enzymes. This also results in overstimulation of cholinergic synapses [69]

Reducing the detrimental Effects of pesticides.

Although perpetual discussions about the extent of harm caused by synthetic fertilizers, it appears that humans are becoming more aware of the use of chemicals, particularly their impact on human well-being and the sustainability of the ecosystem [70]. Such increasing concerns were mostly caused by a lack of faith in crops and manufacturing techniques, as well as government actions aimed at protecting both the environment and human health. Due to the prevalence of variance in poison safety evaluations, scientific data, regulatory standards, and human evaluation are all required when determining whether a chemical may be used safely within its hazardous threshold.

The prospect of reducing the threat to the environment related with the application of pesticides is minimal because growers think less hazard indicates either decreased output or increased input as a consequence of the replacement for chemical additives [71]. Thus, laws striving at mitigating potential hazards linked to chemical application will put expense on farms, thereby influencing agricultural product prices. This is supported by the cost-function-based production model [71], which suggested that the agricultural industry would face significant expenditures as a result of the regulations to limit environmental risk from pesticide use. The higher prices are intimately related to growth in demand for effective pesticides at a specific level of agricultural output, indicating encouraged innovation to improve pesticide quality in conjunction with rising costs.

Concerns about the impacts of pesticide use on human health and the environment motivated the EU to create a 'Thematic Strategy on Sustainable Use of Pesticides' [72]. Furthermore, agricultural experts began developing alternative crop management strategies to limit the harmful consequences of farming (mostly centered on pesticide use for crop protection) on the environment and human health. In particular, the Integrated Crop Management (ICM) comprises instructions to be used by farmer unions to enforce activities for the development of healthy agricultural goods while also respecting the environment [73].

In addition, ICM contains measures for the application of good agricultural practices (GAP), worker safety and cleanliness, product safety, full traceability of measurements, and particular actions for environmental preservation [74]. For the control of pests, ICM encourages the use of complementary methods of pest management (such as crop resistance against insects and fungi, biological control, and other cultural or physical measures) to reduce the animal pest or weed population below its economic injury level and to minimise pesticide impacts on other components of the agro-ecosystem [75]. ICM permits pesticide usage only via an Integrated Pest Management (IPM) program [76].

Pesticides recommended for use in IPM (Integrated Pest) include:

Physiologically effective: High selectivity with rapid action, optimal residual effects, strong tolerance by plants, minimal risk of resistance development.

User-friendly: Low toxicity in both acute and chronic exposures, well-formulated, secure packaging, easy-to-apply methods, and long-term stability during storage.

Environmentally compatible: Minimal toxicity to non-target species, quick breakdown in the environment, low mobility within soil, no food or feed residues exceeding maximum residue limits (MRLs), and low application rates.

Economically viable: Offers an excellent cost-to-benefit ratio for farmers, broad-spectrum effectiveness, compatible with integrated pest management (IPM), innovative product features, competitively priced, and patent-protected [77].

1. Pesticides should be applied at the recommended rate when pests are present, or when preventative treatment is necessary.
2. To achieve economic savings, pesticide doses can be adjusted according to pest population density.
3. Pesticide usage can be minimized by altering agricultural practices to lower pest risks.

When assessing the quantity of active ingredients used or the expenses related to pesticides, these factors should only be considered preliminary estimates, as the amount of active ingredient does not always correspond to environmental impact. Environmentally sustainable and innovative pesticides are often more costly than outdated, hazardous alternatives.

Conclusion

The use of pesticides has significantly increased in recent years, leading to environmental damage, especially through soil and water contamination. Various types of pesticides exist, with organophosphates, organochlorines, carbamates, and pyrethroids being the most widely used, raising concerns for both human health and the environment. Understanding the physical and chemical properties of these pesticides is crucial for assessing their environmental behavior and transformation. Proper management strategies are needed to convert these persistent pesticides into non-toxic compounds before they are released into the environment, as they are often resistant to natural degradation.

The scientific community is working diligently to develop innovative solutions to reduce pesticide pollution. Environmentally friendly approaches, such as bioremediation, offer sustainable alternatives. Techniques like phytoremediation, microalgae-based bioremediation, mycoremediation, and microbial degradation are cost-effective and eco-friendly methods. Microbial degradation, in particular, has gained widespread attention, with microorganisms and their enzymes playing a crucial role in breaking down chemical compounds and synthetic pesticides.

Despite the environmental advantages, microbial degradation faces limitations, as the metabolic pathways followed by microbes are heavily influenced by external factors. Therefore, further research is required in specific areas to improve the effectiveness of this approach. Enzymatic degradation shows promise as a viable method, and ongoing research is essential to identify enzymes capable of breaking down synthetic pesticides. However, microbial degradation tends to be slower and less efficient than traditional bioremediation techniques. To enhance pesticide waste management, it is necessary to identify more potent microbes, discover novel genes, and explore new bioremediation methods.

Genetically engineered microorganisms and biotechnology play a key role in advancing these efforts. The discussion underscores the potential of using pesticide-degrading microorganisms in an environmentally sustainable manner, highlighting the need for further research into identifying effective microbial strains and enzymes to mitigate pesticide risks to the environment and human health.

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