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Effect of Pesticides on Human Health and Biodiversity: A Comprehensive Insight

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ABSTRACT

Pesticides, whether naturally occurring or chemically synthesized, serve to combat various pests across sectors such as food production, forestry, agriculture, and aquaculture, but they also pose risks of toxicity to ecosystems. The World Health Organization classifies pesticides based on their harmful effects, underscoring the importance of public health considerations. By employing them judiciously and understanding their categorization, their usage can be minimized for the benefit of both human health and the environment. This review examines global perspectives on pesticides, including their distribution and environmental impacts, while literature highlights their potential uses, classification and adverse effects on natural systems, water, plants, human health and food preservation. Additionally, eco-friendly management strategies, like bacterial degradation, myco-remediation, phytoremediation, and microalgae-based bioremediation, are discussed as green solutions to mitigate pesticide pollution. The identification of potent microbes, novel genes and biotechnological applications for pesticide waste management is crucial for fostering a sustainable environment.

Key words: Biodegradation, Biodiversity, Human health, Pesticide.

Pesticides, which are chemical agents in a variety of forms, are used to control undesired vegetation, insects, rodents, and fungi. Shedicides, insecticides, fungicides, molluscicides, rodenticides, plant growth regulators, and other supplementary agents are among them (Pathak *et al.,* 2022). In aquaculture, agriculture, food processing and storage, among other industries, they are crucial for ensuring the preservation of food, limiting the spread of disease and safeguarding crops (Sheng *et al.,* 2022). Since pesticides destroy all living things, including plants and animals, both humans and animals are damaged by them (Sheng *et al.,* 2022). Moreover, the chemicals or mixtures of compounds designed to act as defoliants, desiccants, or plant regulators under the US Code of Federal Regulations (CFR) are considered pesticides (Sarker *et al.,* 2023).

According to the Food and Agriculture Organization (FAO) of the United Nations, pesticides are defined as substances or mixtures intended for controlling, preventing, or eliminating animal or human disease vectors, unwanted plants, or animal species affecting food production, handling, sale, storage and transportation (Pathak *et al.,* 2022). Among the many chemical compounds that have been utilized historically to control pests are sulfur compounds and pyrethrum from *Chrysanthemum cinerariaefolium* (Kumar *et al.,* 2021). Pest control underwent a significant change with the introduction of dichloro diphenyl trichloroethane (DDT) in 1939 and its eventual phase-out in the United States (Kumar *et al.,* 2021).

According to estimates, 4.19 million metric tons of pesticides were used globally in 2019 (Alengebawy *et al.,* 2021). China accounted for the largest share of this use, with 1.76 million metric tons, followed by the United States, Brazil and Argentina (Sarker *et al.,* 2023). The World Health Organization (WHO) reported that pesticide use has increased across Southeast Asia, particularly in countries like Vietnam and Cambodia (Sarker *et al.,* 2023). India is a major pesticide manufacturer in Asia, producing 90 thousand tons of organochlorine pesticides annually, including DDT and benzene hexachloride (Kim *et al.,* 2017). Fungicides (17.5%), insecticides (29.5%) and herbicides (47.5%) comprise the bulk of pesticide consumption (Kim *et al.,* 2017). According to estimates, 4.19 million metric tons of pesticides were used globally in 2019 and China accounted for the largest share of this use, with 1.76 million metric tons, followed by the United States, Brazil and Argentina (Pathak *et al.,* 2022). The WHO reports that pesticide use has increased throughout Southeast Asia, particularly in countries like Vietnam, Laos and Cambodia (Pathak *et al.,* 2022). India is one of Asia's top pesticide producers, producing 90 thousand tons of organochlorine pesticides annually, including DDT and benzene hexachloride (Sheng *et al.,* 2022; Mohan *et al.,* 2024).

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Moreover, the impact of pesticides on both human health and biodiversity is a critical issue that demands thorough examination (Punia *et al.,* 2023). Pesticides, while effective in controlling pests and increasing agricultural productivity, pose significant risks to ecosystems and human well-being (Sheng *et al.,* 2022). This comprehensive insight delves into the multifaceted effects of pesticides, exploring their implications on both human health and biodiversity and examines how these chemicals interact with the environment, affecting not only targeted pests but also non-target organisms and entire ecosystems.

Use of pesticide from past to present

Since the Roman era, pesticides have been employed to eradicate pests through methods such as burning sulfur and suppressing the growth of weeds with bitter compounds, ashes and salts (Leng, 2023). Notably, a Roman naturalist recommended using arsenic as a pesticide (Clayton-Smith *et al.,* 2023). In the 1600s, a mixture of honey and arsenic was first used to cure ant infestations and by the late 1800s, farmers in America were using chemicals like nicotine sulfate, calcium arsenate and sulfur to try and manage a range of crop pests (Casimero *et al.,* 2023). The limited application approaches available at the time, however, hampered their efforts (Leng, 2023). Moreover, a modified version of copper arsenate was used to contain the Colorado potato beetle outbreak in the United States in 1867 (Clayton-Smith *et al.,* 2023). The crucial turning point in pesticide invention that took place during and after World War II was the creation and widespread production of a variety of affordable pesticides (Leng, 2023).

Some of the significant discoveries made during this time include Chlordane, Dieldrin, β-Benzene Hexachloride (BHC), 2,4-Dichlorophenoxyacetic acid (2,4-D), Dichlorodiphenyl trichloroethane (DDT) in 1939 and Aldrin (Bertomeu-Sánchez, 2019). Between 1950 and 1955, the emergence of fungicides like captan and glyodin and the introduction of the organophosphate insecticide Malathion occurred concurrently with the discovery of triazine herbicides (Abubakar *et al.,* 2020). Monsanto developed Agent Orange, an experimental herbicide that was employed in the Vietnam War, between 1961 and 1971 (Abubakar *et al.,* 2020). The manufacturing of new pesticides noticeably diminished after 1962 as public awareness of the environmental issues linked to the careless increase of pesticide use, as a result, the manufacturing of new pesticides indeed decreased as awareness grew regarding the environmental and health risks associated with their indiscriminate use (Abubakar *et al.,* 2020).

Moreover, in 1962, American scientist Rachel Carson wrote in her book “Silent Spring” that DDT spraying in fields caused sudden mortality of non-target animals through direct or indirect poisoning (Carson, 2015). Pesticide research and development came to an end as a result of the book “Silent Spring”. Still, it resulted in the creation of “integrated pest management” (IPM) in the late 1960s, which is a pest control technique that employs biological predators or parasites (Epstein, 2014). While Integrated Pest Management (IPM) has demonstrated efficacy in lowering pest populations, particularly during epidemics, chemical pesticides remain the recommended choice (Delaplane and Mayer, 2000). Concerning chemical insecticides as per the History of Pesticide Use (1998), pyrethroids, sulfonylureas, and synthetic fungicides like metaxyl and triadimefron were among the new pesticide classes that were launched during the 1970s and 1980s (Edström *et al.,* 2000). In 1972, the USA entirely outlawed DDT and imposed restrictions on endosulfan, dieldrin and lindane and since then, other pesticides that are prohibited have been added to the list (Carson, 2015). Afterwards, the European Union banned neonicotinoid insecticides in 2013 (Delaplane and Mayer, 2000).

According to Macneale *et al.* (2010), there is a significant risk to fish species, including salmon, as well as primary producers and macro-invertebrates, when pesticides are heavily applied in aquatic habitats. Pesticide importation and distribution within Pakistan was handled by the Plant Protection Department of the Government of Pakistan before to 1980. A prepayment system with subsidies was used for the purchase of pesticides. That said, the private sector took on this role in 1980. Pesticide imports and usage in Pakistan have been steadily rising ever since. According to Jabbar and Mallick (1994), pesticide registration is routinely renewed to guarantee its safe use. Nowadays, biological pest control techniques are becoming more and more common. This method, referred to as bioeffector-based pest management, uses a variety of living organisms as biocontrolling agents. These biocontrolling substances are also known as biologic insecticides. Insect growth regulators (IGRs) are an example of a bio-rational pesticide since they are hormones that regulate insect growth without posing a threat to non-target organisms (Clayton-Smith *et al.,* 2023; Riedo *et al.,* 2023).

Classification of pesticides

It is generally agreed upon that pesticides are necessary for controlling human diseases and preventing crop losses. Depending on how they work as agents to get rid of, discourage, or control pests, they can be categorized (Schmolke *et al.,* 2010). Nevertheless, pests and insects have become resistant to commercial pesticides as a result of their overuse. According to Speck Planche *et al.* (2012), recent developments have resulted in the creation of insecticides that target several species. These days, chemical pesticides and insecticides are gradually taking the lead as the main techniques for controlling pests. According to Gentz *et al.* (2010), the utilization of chemical pesticides in conjunction with natural enemies that can enhance integrated pest management by providing a thorough preventive and corrective strategy (Thundiyil *et al.,* 2008). A multitude of parameters, including as life history, features, time of application, population composition, and landscape architecture, influence how pesticides affect populations in addition to exposure and toxicity (Schmolke *et al.,* 2010). Nicotinic acetylcholine receptors for neonicotinoids, gamma-aminobutyric acid receptor channels for polychlorocyclohexanes and fiproles, voltage-gated sodium channels for dichloro-diphenyl-trichloroethane and pyrethroids and acetylcholinesterase for organophosphates and methylcarbamates are important targets in the nervous systems of insects for the development of neuroactive insecticides (Casida and Durkin, 2013).

More often used neonicotinoid pesticides have been connected to several toxicity problems (Abubakar *et al.,* 2020). Globally, pesticides are categorized into a number of classes based on the purposes for which they are manufactured. Nematicides, rodenticides, molluscicides, herbicides, insecticides, fungicides, and regulators of plant growth are some of these categories. Pesticides have caused significant harm to the ecosystem and have sparked substantial worries about biodiversity and human health due to their overuse (Singh *et al.,* 2010). It is well known that pesticides are highly polar, heat stable and soluble in water, which makes it challenging to mitigate their harmful effects. In addition to raising worries about toxicity for people in the agricultural industry, they also contribute to toxicity in the fields of industry and public health. Depending on the species they target, pesticides can have negative effects on wildlife, natural flora and aquatic ecosystems (Abubakar *et al.,* 2020).

Risk associated with pesticides use

Pesticide use has had more detrimental impacts than beneficial ones, endangering non-target animals and biodiversity in both terrestrial and aquatic ecosystems. Eighty-nine per cent of sprayed pesticides can evaporate within a few days of application, usually when the chemical is being sprayed (Tudi *et al.*, 2022). Variable pesticides can pose a threat to animals that are not their intended target when they evaporate into the sky. One example of this is herbicides that evaporate from treated plants and harm nearby flora (Jallow *et al.,* 2017). Pesticide overuse has threatened rare species such as bald eagles, ospreys and peregrine falcons, and has caused the extinction of several terrestrial and aquatic animal and plant species (Clarke *et al.,* 1997). Additionally, these materials have accumulated to dangerous levels in the air, water and soil. Herbicides and fungicides are the second most harmful type of pesticides, which are categorized based on their degree of toxicity. Pesticides can enter natural ecosystems in two different ways, depending on how soluble they are: Pesticides that dissolve in water can contaminate streams, rivers, lakes and other bodies of water by penetrating into the groundwater table and posing a threat to non-target animals (Tudi *et al.,* 2022).

Contrarily, fat-soluble pesticides enter animal bodies through a process known as “bioamplification,” whereby they accumulate in fatty tissues and spend a significant length of time in food chains (Daley *et al.,* 2014). Primary consumers like grasshoppers, which are at lower trophic levels in the food chain, only absorb a minimal amount of pesticide in their bodies. Shrews devour a large number of grasshoppers as secondary consumers, which raises the concentration of pesticides in their bodies. An owl’s body contains much more insecticide when it eats shrews and other animals (Bearhop *et al.,* 2000). A significant rise in the concentration of pesticides within the body occurs. Thus, a mechanism known as bioamplification explains why pesticide concentrations increase as one moves up the trophic pyramid (Daley *et al.,* 2014). This process disrupts the ecosystem as a whole by making higher trophic level animals more toxic and increasing their death rate. The population of secondary consumers, like shrews, rises as a result of this imbalance, while that of main consumers, such grasshoppers, decreases (Tudi *et al.,* 2022).

Threats to biodiversity

It is important to recognize the risks associated with using these substances excessively. Analyzing how pesticides affect the populations of terrestrial and aquatic plants, animals, and bird species is vital (Abubakar *et al.,* 2020). Because pesticide accumulation directly affects predators and prey-seeking birds, it is especially concerning when it occurs in food chains. Furthermore, pesticides have the indirect effect of reducing the number of weeds, bushes, and insects that provide food for species at a higher level. Decreases in the numbers of uncommon animal and bird species have also been connected to the use of pesticides, herbicides and fungicides (Schiesari *et al.,* 2013). Pesticide exposure may have effects on terrestrial plants that are less harmful than the intended elimination of unwanted vegetation. For instance, phenoxy herbicides can harm neighboring trees and shrubs when they drift or evaporate (Abubakar *et al.,* 2020). As a pesticide, glyphosate has been shown to decrease seed quality (Duke, 2018) and increase plants’ susceptibility to disease (Daley *et al.,* 2014). Herbicides such as sulfonylureas, sulphonamides and imidazolinones can negatively impact the productivity of natural plant communities, animals and non-target crops, even at low concentrations (Sammons and Gaines, 2014). On top of that, pesticides are bad for animal populations on land. Application of broad-spectrum pesticides like carbamates, organophosphates and pyrethroids can result in significant declines in the population of valuable insects like bees and beetles. Surprisingly, compared to conventional farms, organic farms have been found to have healthier insect populations. According to Johnson *et al.* (2006), honey bees may also suffer when pyrethroids are used in conjunction with imidazole or triazole fungicides. There is a toxicity risk to bees from neonicotinoid insecticides such as imidacloprid and clothianidin.

Bee learning capacities have been shown to be negatively impacted by imidacloprid, even at low concentrations (Wamhoff and Schneider, 1999). As well as negatively affecting bee foraging behavior. As much as thirty percent of food production depends on bee pollination, the widespread use of neonicotinoids in the early twenty-first century led to a sharp fall in honey bee populations, which posed serious challenges for the food sector. A considerable quantity of neonicotinoids and other pesticide residues have been found in honey and beeswax that are collected from commercial beehives (Johnson *et al.,* 2006). Of the bird populations that have declined throughout millennia, 20% to 25% have been affected by pesticide use. One factor in birds' demise is the accumulation of chemicals in their tissues. Bald eagle population declines in the USA were mostly caused by exposure to DDT and its metabolites (Tudi *et al.,* 2022). Because earthworms are an essential part of birds' and mammals' diets, fungicides have an indirect effect on their populations. Granular pesticide formulations are frequently mistaken for food grains by birds. Organophosphate insecticides have been shown to poison raptors in agricultural fields and are extremely hazardous to birds. Pesticides can cause behavioral changes in birds by disrupting their neural systems even at sublethal levels (Tudi *et al.,* 2022). Applied as granulars, incorporated or injected into the soil, liquid sprays on crops or soil, or seed treatments are some of the ways that pesticides can be used. Chemicals that are applied on surfaces can degrade, disperse, volatilize, or leak into groundwater and surface water (Kim *et al.,* 2017).

They can be absorbed by plants or soil organisms or persist in the soil (Tudi *et al.,* 2022). The main issue related to excessive pesticide usage is their seepage into the soil, which has adverse effects on soil-dwelling microorganisms. These microorganisms are essential for aiding in nutrient absorption, breaking down organic matter, and enhancing soil fertility, all of which ultimately benefit humans who heavily depend on plants (Wamhoff and Schneider, 1999). However, the overuse of pesticides can lead to severe consequences, potentially resulting in a situation where these organisms become nonviable, leading to soil degradation. Triclopyr is poisonous to some mycorrhizal fungal species, although oxadiazon decreases the quantity of fungal spores (Kim *et al.,* 2017). Due to their ability to detect soil contaminants and increase soil fertility, earthworms are important members of the soil ecosystem (Wamhoff and Schneider, 1999). Earthworms are sadly harmed by pesticides as well, mostly as a result of contact with tainted soil pore water (Pathak *et al.,* 2022).

Impact on soil and water

Beaumelle *et al.* (2023) posit that pesticide applications in agricultural settings may have an effect on the leaching process, hence influencing the associated chemical, physical, and biological properties of sediment. Pesticides end up everywhere in the soil and water because of a variety of farming practices. The duration of their presence in the environment, which can span weeks, months, or even years, can be influenced by various parameters such as pH, temperature, moisture content, soil texture, concentration of mineral and organic components, and climate change (Münzel *et al.,* 2023). Given that the mobility and stability of chemical compounds are necessary for their leaching and seepage, polluted water can also happen (Pereira *et al.,* 2016).

Impact on natural system

About one-third of the world's agricultural supply is protected by pesticides, however there are negative effects on ecosystems from their widespread use (Gill and Garg, 2014). Because of improper use, mishandling, or ignorance that leads to abuse and overuse, pesticides can accumulate and cause harm in surroundings outside of agricultural regions (Münzel *et al.,* 2023). Users frequently fail to follow label directions about usage and safety precautions, such as wearing protective eyewear and rubber gloves to minimize exposure (Münzel *et al.,* 2023). There are environmental problems as a result of these chemicals' diverse effects on non-target creatures (Gill and Garg, 2014). Applications on the ground as well as spraying are important sources of air pollution resulting from persistent organic pesticides (POPs). Spray-borne insecticides with half-lives of several days to more than a month are absorbed by aerosol particles, depending on their gas phase reactivity. POPs are airborne pollutants that change through photochemical reactions and oxidation from their original state to extremely toxic versions (Münzel *et al.,* 2023).

The spread of these pesticides (POPs) is dependent on a number of factors, including their limited solubility in water and environmental factors such as humidity and temperature (Pathak *et al.,* 2022). Pesticides can contaminate soil in a variety of ways, while their primary purpose is to protect crops. As pesticides move through the soil, they are affected by a number of factors, including the specific pesticide and groundwater conditions. Other factors include improper application, inadequate dosage guidance, significant runoff into water bodies and other factors. This contamination, according to Sheng *et al.* (2022), lowers the quality of drinking water. Organochlorine pesticides (OCPs) have been used extensively worldwide to combat agricultural pests and vector-borne diseases such as malaria and dengue. Long-lasting in natural systems are non-volatile chemicals such as organochlorine pesticides. Their usage poses a challenge because they are so frequently encountered in natural environments. Applying these chemicals carelessly could have negative effects on drinking water supplies, human health and the environment (Sarker *et al.,* 2023).

Over the years, exposure to organochlorine pesticides (OCPs) has been linked to immune system disorders, cancer, neurological disorders, birth abnormalities, and reproductive issues (Sarker *et al.,* 2023). Water, both surface and ground, must be free of pesticides. Pesticides can enter aquatic systems through both leaching processes and surface runoff. Plants absorb these materials in the soil, where they undergo a series of chemical reactions, before seeping into groundwater. The likelihood of pesticide contamination in water increases with rainfall. The health of humans and other living things is at danger due to pesticide contamination of groundwater, which lowers the quality of the water (Sarker *et al.,* 2023).

There are several difficulties in getting rid of pesticides from groundwater. There are detrimental impacts of pesticides on ecosystems and people when they are discovered in drinking water. As per Sheng *et al.* (2022), the World Health Organization (WHO) reports that around one million individuals get acute pesticide poisoning every year as a result of exposure. Pesticide use needs to be controlled, even if it is essential for increasing agricultural output. To reduce the disturbance of the ecosystem that pesticides cause, it is imperative to apply Integrated Pest Management (IPM) techniques for pest management (Kumar *et al.,* 2021).

Impact on plants

Chemical pesticides are now a modern farmer's best friend when it comes to managing a wide range of agricultural problems, including weeds, insects, bacteria, fungi, mollusks, rodents and more. Pesticides are used to increase agricultural productivity as the world's population grows and the demand for food supply rises (Alengebawy *et al.,* 2021). These insecticides are essential for protecting agricultural land's crops and lowering the possibility of harm during post-harvest storage. Their usage is limited by their detrimental effects on soil quality in agricultural areas, despite their great effectiveness in suppressing plant and human illnesses like typhoid and malaria. This worry underscores the significance of properly weighing their detrimental effects. During the 1960s, a number of highly developed countries decided to impose limitations or prohibitions on the use of pesticides (Alengebawy *et al.,* 2021). However, due to the widespread application of pesticides, pests and insects are developing resistance to certain modified pesticides like DDT, allowing them to evade their effects. Using insecticides creates a barrier that keeps other insects from consuming the pods and from entering them. However, damaged pods may either produce very few or very poor-quality, useless seeds (Pathak *et al.,* 2022). According to studies, chitosan applied during the early stages of growth encourages plant growth and development, which raises the yield of rice and soybean seeds (Alengebawy *et al.,* 2021).

Impact on human health

Pesticide exposure in people can happen both directly and indirectly. Pesticides can immediately damage the skin, eyes, mouth and respiratory system, for example, when they are sprayed on crops (Pathak *et al.,* 2022). This may result in sudden reactions such rashes, headaches, irritability, vomiting and sneezing. The length and intensity of exposure to certain pesticides affect how seriously they affect people. Usually, the body eliminates pesticides through the secretory glands, bile and urine. However, long-term ingestion of fruits and vegetables grown in pesticide-contaminated soil and water can accumulate toxins in bodily organs, causing chronic illnesses like diabetes, cancer, necrosis, asthma, reproductive disorders and heart disease (Ansari *et al.,* 2021).

Notwithstanding the lack of clarity surrounding their underlying molecular mechanisms, quaternary nitrogen compounds, including paraquat, have been linked to neurodegenerative diseases like Parkinson's (El-Nahhal *et al.,* 2013). As per Bernardes *et al.* (2015), carbamate insecticides function as indicators of neurotoxicity by preventing acetylcholinesterase (AChE) from functioning. Many pesticide-induced malignancies, the most prevalent of which is breast cancer, have been linked to organophosphorus compounds like parathion and malathion, which obstruct cellular growth and proliferation (Ansari *et al.,* 2021). Moreover, autoinhibitory M2 muscarinic receptors in the parasympathetic nervous system have been found to influence human epigenetic methylation patterns (Ansari *et al.,* 2021).

Occupational pesticide exposure is linked to substantially higher genetic damage than smoking and alcohol use, according to Nascimento *et al.* (2022). This emphasizes the alarming reality that there is a greater risk of pesticide exposure than there is from stopping to smoke. A meta-analysis looking into the likelihood of random DNA damage in farmers exposed to pesticides found that the risk of such damage is around 4.63 times higher in the pesticide-exposed group than in the control group (Nascimento *et al.,* 2022). This meta-analysis included 42 studies with 2,885 individuals in the exposed group and 2,543 in the control group overall. This study demonstrated, in contrast to prior research, that the amount of DNA damage caused by pesticides was not affected by the type of pesticide used, the individual's age, or gender.

Those who live close to farming areas but do not work in agriculture are potentially at risk of genetic damage caused by pesticides since they are passively exposed to these chemicals. Pesticide concentrations in the bloodstream and DNA damage are generally higher in non-occupational pesticide exposure scenarios. According to Gürbüz *et al.* (2018), pesticides cause oxidative stress, which damages DNA because of their oxidative characteristics. Scholarly research indicates that non-occupational pesticide exposure is especially dangerous for the elderly, women and kids. Analyses of toddlers' peripheral blood lymphocytes from pesticide-sprayed areas showed increased numbers of micronuclei (MN), oxidative damage and breakage in DNA strands (Nascimento *et al.,* 2022). Pyrethroids are a common pesticide used in commercial and agricultural contexts. Non-occupational exposure to these pesticides usually comes *via* residues in contaminated food and air (Ansari *et al.,* 2021). Moreover, various impact of pesticides on human health and environment are indexed in Fig 1.

Eco-friendly management of pesticide as bioremediation

Pesticides can release more dangerous substances throughout the physical and chemical purification process, which makes the procedure dangerous and expensive. Eco-friendly bioremediation techniques are available to remove dangerous toxins in order to preserve a sustainable environment with a healthy ecosystem (Desisa *et al.,* 2022). Bioremediation is an economical and ecologically sustainable way to treat environmental problems by using plants, algae, fungi, bacteria and their interactions. Many environmentally friendly methods are used in modern pesticide remediation procedures, such as phytoremediation, microalgae bioremediation, mycoremediation, and bacterial pesticide degradation (Singh *et al.,* 2020). The role of microorganisms and their enzymes in the degradation of several pesticides has been well-researched and documented (Bano *et al.,* 2021).

These steps include compound activation, detoxification, co-metabolism and mineralization. Gangola *et al.* (2022) reported on the finding of hydrolases and oxygenases, as well as their functions in the biodegradation of pesticides. Numerous elements can influence the process of pesticide breakdown, including microbial culture, cultivation techniques, inoculum size, exposure to high pesticide concentrations, adaptability, interactions in the rhizosphere, and sensitivity to environmental conditions. Research has focused on the technique of microbial cellular immobilization (CI), which uses a variety of materials to enable the extended survival of bacteria. The use of microbial cells as CI has been more prevalent in recent research, helping to improve the long-term sustainability and effectiveness of methods in pesticide-contaminated areas. For pesticide biodegradation, this strategy has potential. By utilizing the mutually beneficial relationship between degrading bacteria and cellular immobilization (CI) technology, waste management can be sustainably addressed while managing contaminants (Gangola *et al.*, 2022).

According to Conde-Avila *et al.* (2021), although CI presents an environmentally responsible option, it has certain drawbacks, such as the influence of microbial interactions with the immobilization substance on microbial survival. But when it comes to clearing other pesticides including cypermethrin, endosulfan, carbaryl, atrazine, difenoconazole and carbofuran, CI proves to be a more effective method than free cells, with greater clearance percentages and improved efficiency. The immobilization techniques or materials used to support CI enhance its effectiveness (Conde-Avila *et al.*, 2021). Additionally, the breakdown and photodegradation processes have a big impact on how pesticides appear and move (Conde-Avila *et al.,* 2021). Sandier soils have less capacity to reduce pesticide availability through adsorption than soils with higher organic matter content (Gangola *et al.*, 2022). Moreover, synthesis, production, uses, effects and eco-friendly management of pesticides are indexed in Fig 2.

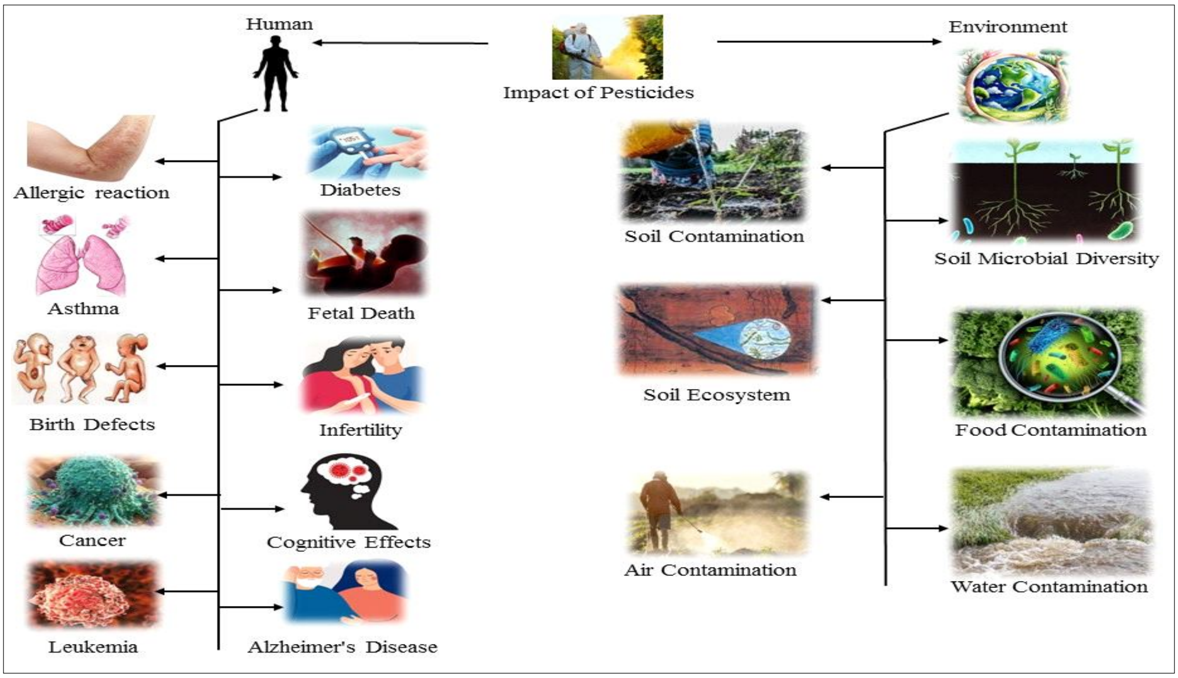

Fig 1: Various impact of pesticides on human health and environment.

However, a list of pesticides degrading microorganisms are indexed in Table 1 and the bacterial enzymes, responsible for the degradation of pesticides are indexed in Table 2.

Registeration and safety

The licensing process for pesticides is quite complex, involving numerous legal and administrative steps that cost a lot of money and effort (Wong-Villarreal *et al.*, 2016). Knowledge from pesticide manufacturers as well as the regulating body are required. The safety of both active and inert components used in pesticide manufacture must be ensured, according to Priyanka *et al.* (2024), by conducting a thorough assessment of the possible consequences of

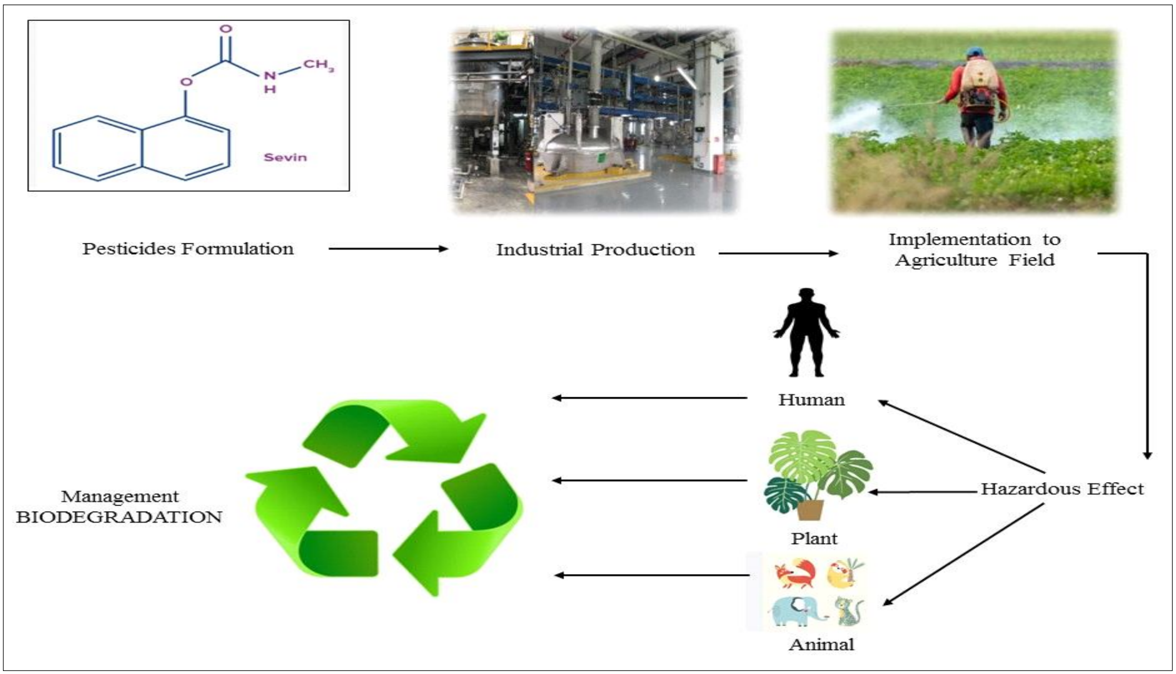

Fig 2: Synthesis, production, uses, effects and eco-friendly management of pesticides.

Table 1: Pesticides degrading microorganisms.

Microorganisms genus	Pesticide	Reference
Bacillus, Pseudomonas, Arthrobacter, Micrococcus, Flavobacterium, Cupriavidus, Burkholderia, Brevundimonas,Spirulina, Synechocystis	Chlorpyrifos	Saravanan *et al.*, 2022
Pseudomonas, Flavobacterium, Pseudomonas, Arthrobacter, Agrobacterium, Bacillus, Xanthomonas	Parathion	Saravanan *et al.*, 2022
Pseudomonas, Bacillus, Plesiomonas	Methyl parathion	Huch *et al.*, 2022
Pseudomonas, Alcaligene, Bacillus, Rhizobium, Agrobacterium, Arthrobacter, Geobacillus	Glyphosate	Huch *et al.*, 2022
Nocardiodes, Agrobacterium, Pseudomonas, Pseudomonas, Flavobacterium, Nocardiodes	Coumaphos	Blatchford *et al.*, 2012
Pseudomonas, Bacillus, Arthrobacter, Clavibacter	Monocrotophos	Khanna *et al.*, 2019
Flavobacterium, Arthrobacter, Burkholderia	Fenitrothion	Kim *et al.*, 2009
Micrococcus, Bacillus, Flavobacteria, Pseudomonas, Phlebia, Mortierella, Trametes, Aspergillus, Fusarium, Klebsiella, Acinetobacter	Aldrin, Dieldrin, Endosulfan	Bose *et al.*, 2021
Trichoderma, Stenotrophomonas, Pseudomonas, Sphingobacterium, Trichoderma, Rhizopus	Dichlorodiphenyl -trichloroethane	Bose *et al.*, 2021
Microbacterium, Paracoccus, Streptomyces, Streptomyces, Pleurotus, Phanerochaete	Lindane	Huch *et al.*, 2022
Achromobacter, Diaphorobacter	Carbafuron, Emamectin Benzoate, Thiamethoxam	Benítez-Villa and Ortiz-Hernández, 2023
Priestia	Organophosphates	Kilonzi and Otieno, 2024

Table 2: Bacterial enzymes, responsible for the degradation of pesticides.

Pesticides	Enzyme	Bacteria	Reference
Glyphosate	Oxidoreductase	*Pseudomonas*, *Agrobacterium*	
Endosulfan, aldrin, malathion, Dichlorodiphenyl trichloroethane, endosulfate	Monooxygenases	*Mycobacterium, Arthrobacter*	
Hexachlorobenzene, Penta chlorobenzene	Cytochrome P450	*Pseudomonas putida*	
Trifluralin	Dioxygenases	*Pseudomonas*	Pathak *et al.,* 2022; Benítez-Villa and Ortiz-Hernández, 2023
Hexachlorocyclohexane	Haloalkane Dehalogenases	*Sphingobium*	
Chloro-S-triazine	Atrazine Chlorohydrolase	*Pseudomonas*, *Nocardioides*	
Hexachlorocyclohexane	Ligase	*Sphingobium*	
2,4-dichlorophenoxyacetic acid	Herbicide-Degrading α-Keto Acid-Dependent (TfdA)	*Ralstonia*	
Pyridyl-oxyacetic acid	TfdA, Dicamba monooxygenase	*Ralstonia, Pseudomonas*	
Phosphotriester	Phosphotriesterases	*Pseudomonas, Agrobacterium, Flavobacterium*	

pesticide application on human health and the environment. Registration plays a key role in pesticide control by guaranteeing that products on the market are authorized and used exclusively for the intended purposes (Wong-Villarreal *et al.,* 2016). It also gives regulatory agencies the authority to keep an eye on a variety of areas, such as pesticide advertising, product quality, pricing, packaging, labeling, safety measures and labeling, in order to safeguard the interests of consumers (Onwona Kwakye *et al.,* 2019). Before filing the application or data report, the maker or registrant must carry out a number of tests and investigations pertaining to the chemistry of the product. These assessments examine risks to people, animals, and non-target species, as well as forecast how the pesticide will behave once it is discharged into environment (Onwona Kwakye *et al.,* 2019).

CONCLUSION

Pesticide usage has surged recently, causing significant environmental harm, especially in water and soil contamination; prevalent types like organophosphates, organochlorine, carbamate, and pyrethroids raise human and environmental concerns. Understanding pesticide properties is crucial for assessing their impact and transformation in the environment, necessitating proper management strategies to convert them into non-toxic compounds before release. Bioremediation methods like phytoremediation, microalgae bioremediation, myco-remediation, and microbial degradation offer eco-friendly and cost-effective solutions, though they require further research due to limitations such as metabolic influences. Enzymatic degradation, a promising approach, underscores the need for ongoing research to identify enzymes capable of breaking down synthetic pesticides, alongside the search for potent microbes and novel genes for effective waste management. Genetically engineered microorganisms and biotechnology also hold promise in emphasizing the importance of continued studies to mitigate pesticide risks to the environment and human health.

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