An Insight to Pesticides

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1 Introduction

Environmental pollution has become a global issue, raising serious concerns about its harmful effects on human health and the stability of ecosystems (Khan et al., 2010; Nasrollahi et al., 2020). Although pollution largely stems from human activities, it is essential to weigh the associated benefits and risks rather than place blame outright (Ahmad et al., 2024; Mahmood et al., 2015). Pesticides, commonly used in agriculture to control pests, insects, and weeds, play a crucial role in both modern farming and health practices (Carvalho, 2017; Mahmood et al., 2015; Umetsu & Shirai, 2020). Each year, around 3 billion kilograms of pesticides is utilized worldwide, with an estimated cost of approximately 40 billion USD (Zhang et al., 2011). Various types of pesticides—including herbicides, insecticides, fungicides, and nematicides—are used extensively to boost crop yields, minimize harvest losses, and increase food supplies. However, the widespread and often unregulated use of these chemicals has led to significant environmental harm and negative health effects. These substances can accumulate in ecosystems, disrupting natural balances through bioaccumulation (Mahmood et al., 2015; Sharma et al., 2019). Due to their non-biodegradable nature, they persist in the environment for prolonged periods,

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presenting considerable biohazards (van Dijk, 2010; Hashimi et al., 2020). The modern surge in chemical use has had a profound impact on the biosphere, affecting life quality (Pimentel, 2005). A wide array of chemical agents is used to control unwanted plant and insect species, with examples like dichloro-diphenyl-trichloroethane (DDT) and its metabolite dichlorodiphenyldichloroethylene (DDE) serving to manage vector-borne diseases such as malaria, dengue (WHO, 2012), leishmaniasis (Claborn, 2010), Japanese encephalitis (JE) (Simon et al., 2024), and schistosomiasis (Schmolke et al., 2010). Epidemiological research has shown that pesticide exposure can harm several organs, including the liver, brain, lungs, and colon. Studies have also linked pesticides to severe diseases like cancer, as they generate reactive oxygen species (ROS) that decrease antioxidant levels and weaken the body's defenses against cellular oxidative damage. Lipids, proteins, and nucleic acids are especially vulnerable to this oxidative imbalance, which interferes with cellular signaling and may cause chronic health issues, including reproductive disorders in both humans and animals (Ahmad et al., 2024; Moon et al., 2009; Oluwole & Cheke, 2009; Pesticide Action Network, 2010). The oxidative imbalance caused by pesticides contributes to various diseases and disrupts natural equilibrium.

While pesticide use has improved agricultural productivity, it has exacted a heavy toll on human health and the environment. Unrestricted application of these chemicals has been linked to numerous health risks, including organ damage, cancer, reproductive issues, and ecological imbalance (Abong'o et al., 2014; Buczyńska & Szadkowska-Stańczyk, 2005; Carvalho, 2017; Schreinemachers & Tipraqsa, 2012). The non-biodegradability of pesticides only intensifies these issues, as they linger in ecosystems and present long-term hazards. As agriculture advances, it is crucial to prioritize environmental conservation and human health protection.

2 Pesticides

Pesticides are a broad category of chemical substances, biological agents, or their mixtures introduced into the environment to prevent, manage, or eliminate populations of harmful insects, weeds, rodents, fungi, and other pests. These substances are essential in modern agriculture and public health, playing a central role in protecting crops and controlling disease vectors. Pesticides achieve pest control through various mechanisms, including attraction and toxic effects, to suppress or eradicate target organisms. Pests, which can include any species threatening food security, health, or human welfare, are countered using a wide range of pesticides, from natural compounds derived from organisms or environmental sources to synthetic chemicals (Mahmood et al., 2015; Sharma et al., 2019).

Pesticides are categorized by type, with common classes including organochlorines, carbamates, organophosphates, pyrethrins, and neonicotinoids, which collectively make up a large portion of currently applied pesticides (Foundation, 2018). These formulations consist of active ingredients along with inert substances, contaminants, and sometimes impurities. Once released, pesticides degrade into metabolites, which can, in some cases, be more toxic than the original compounds

(Carvalho, 2017). Notable for their mobility, persistence, and bioaccumulation potential, pesticides pose significant environmental risks (Fenik et al., 2011). Despite their effectiveness in pest control, the use of herbicides, fungicides, insecticides, acaricides, nematicides, antimicrobials, and rodenticides often comes with drawbacks. Non-selective pesticides may harm non-target species, and the rise of pesticide-resistant pests over time reduces the efficacy of these chemicals (Mahmood et al., 2015).

3 History of Pesticides

Crop cultivation has been a foundational element of human civilization for thousands of years, originating in the Fertile Crescent in Mesopotamia around 10,000 years ago. Throughout history, agriculture has faced continuous challenges from pests and diseases threatening food production. The first known use of pesticides dates back roughly 4500 years to the Sumerians, who used sulfur compounds to control insects and mites (Umetsu & Shirai, 2020). Additionally, the ancient Hindu scripture "Rig Veda," composed around 4000 years ago, mentions poisonous plants employed for pest control (Foundation, 2018).

The evolution of pesticide development can be divided into five phases: pre-1000 CE (early pest management practices), 1000–1850 (use of plant, animal, or mineral derivatives), 1850–1940 (introduction of inorganic products and industrial byproducts), 1940–1970 (adoption of synthetic organic compounds), and post-1970 (development of lower-risk synthetic organics) (Foundation, 2018; Mahmood et al., 2015; Sharma et al., 2019). Following World War II, the advent of organic chemistry significantly advanced pesticide science, marking the start of industrialized pesticide production. Over the last century, numerous pesticide companies have formed in Europe and the United States, with many consolidating in the twenty-first century. This growth in production has fueled global pesticide use, with Japan emerging as a leading producer.

The development of synthetic organic pesticides has focused on three main goals: creating highly effective pesticides that require minimal dosage, designing pesticides that readily degrade to reduce environmental persistence, and developing selective agrochemicals that target specific pests without affecting non-target species (Umetsu & Shirai, 2020). The first goal has resulted in reduced active ingredient quantities necessary for pest control, lessening environmental impact. The second goal has contributed to lower pesticide residue levels in both crops and the environment (Kraus, 1995). The third goal aims to produce compounds that specifically target pests while sparing beneficial organisms, leading to safer, eco-friendly pesticides (Hatfield, 2004).

These strategies have become increasingly important in recent years. For instance, pesticides in the 1930s and 1950s required much higher application rates—ranging from 1 to 10 kg/ha for active ingredients like dinitro-ortho-cresol (DNOC), thiuram, and DDT—resulting in significant environmental impacts. However, advancements in pesticide efficacy now allow for effective pest control at

Table 1 Evolution of pesticides usage

Year	Event
1867	Paris Green (form of copper arsenite) was used to control Colorado potato beetle outbreak
1885	Introduction of a copper mixture by Professor Millardet to control mildew
1892	Potassium dinitro-2-cresylate was produced in Germany
1939	DDT discovered by Swiss chemist Paul Muller; organophosphate insecticides and phenoxyacetic herbicides were discovered
1950s	Fungicides captan and glyodin and insecticide malathion was discovered
1961–1971	Agent Orange was introduced
1972	DDT officially banned
2001	Stockholm Convention

Source: Mahmood et al. (2015)

application rates as low as 10 g/ha (Umetsu & Shirai, 2020; Zadoks & Waibel, 2000). In the past decade, a variety of new pesticides have emerged, including fungicides, insecticides, nematicides, acaricides, herbicides, and biopesticides. Among the 105 chemical pesticides developed or in progress, many are considered safe for human health and environmentally friendly, comprising 43 fungicides, 34 insecticides/acaricides, 6 nematicides, 21 herbicides, and 1 herbicide safener. Although advancements in genomics, structure–activity relationship studies, and chemical biology have propelled pesticide research, only a few breakthroughs have reached widespread application (Joseph Shaba et al., 2019) (Table 1).

4 Production of Pesticides: A Multifaceted Process

The manufacturing of pesticides involves a sequence of carefully orchestrated steps, each essential to producing effective chemical formulations. This process begins with the precise selection of raw materials specific to the type of pesticide being manufactured (Brown, 2006; Llewellyn et al., 2016). These materials undergo synthesis to create the active ingredient, which is crucial for the pesticide's effectiveness. This synthesis stage typically involves intricate chemical reactions that require skilled expertise to achieve the desired compound (Alosaimy et al., 2023; Wang et al., 2015).

After the active ingredient is synthesized, it is formulated into a usable form, commonly as a liquid suspension or emulsifiable concentrate. This formulation step includes combining various inert ingredients such as solvents, emulsifiers, additives, and stabilizers—to enhance the pesticide's stability, effectiveness, and user-friendliness (Abubakar et al., 2020; Carvalho, 2017). Quality control measures are rigorously applied throughout production to ensure that the final product upholds high standards for purity, potency, and safety. These controls involve thorough testing of all materials and products to identify and address potential contaminants or inconsistencies. In the final stage of production, the concentrated pesticide is diluted to an appropriate concentration for its intended use, balancing effective pest control with minimized risks to human health and the environment (Abong'o et al., 2014).

5 Mode of Action of Pesticides

A pesticide's mode of action, or mechanism of action, refers to the specific biochemical interactions through which it disrupts essential biological processes in target organisms. This classification uniquely focuses on the biological pathways that pesticides affect, rather than simply categorizing them by pest type, physical properties, or chemical makeup (Joseph Shaba et al., 2019; Zoccali et al., 2009).

Pesticides can affect target organisms via two main routes: systemic and non-systemic. Systemic pesticides are absorbed by plants or animals and distributed internally, allowing them to impact areas that were not directly treated with the pesticide (Aktar et al., 2009). Conversely, non-systemic or contact pesticides act only when they come into direct contact with the pest, delivering effects at the point of application.

6 Classification of Pesticides

Pesticides can be categorized based on the specific types of pests they are designed to control. Examples include insecticides, fungicides, herbicides, rodenticides, biopesticides, and nematicides (Foundation, 2018) (Fig. 1).

(i) Fungicides are chemical agents designed to prevent and treat fungal infections in crops by targeting and eliminating harmful fungal pathogens. They are primarily classified into two types: inorganic and organic fungicides. Inorganic fungicides include substances like Bordeaux mixture and mercuric chloride, while organic fungicides encompass a wider variety of compounds, such as dithaneS-21, dithaneM-22, and dithaneZ-78 (all carbamates), as well as azoxystrobin, fenpropimorph, iprodione, tebuconazole, thiram, and ziram. Though ziram is effective against fungal pathogens, its toxicity poses considerable risks to aquatic zooplankton, impacting ecosystem health.

(ii) Herbicides and weedicides are chemical agents utilized to control unwanted plants or weeds in agriculture. These substances are classified based on their mode of action and application technique. Selective herbicides are designed to target specific plant species without affecting others, whereas non-selective herbicides eliminate all types of vegetation. Contact herbicides act on plant tissues immediately upon contact, while translocated herbicides are absorbed and spread throughout the plant. Herbicides can be applied to foliage or incorporated into the soil for effective weed control. Notable herbicide classes

Fig. 1 Different types of pesticides

include butachlor, chlorsulfuron, diuron, glyphosate, linuron, metsulfuron methyl, metamitron, triazines (like atrazine and simazine), carbamates (e.g., thiocarbamates, phenyl carbamates), and auxin derivatives (2, 4-D and 2, 4, 5-T). Agent Orange, a notorious herbicide mix of 2, 4-D and 2, 4, 5-T, was used during the Vietnam War. Certain herbicides, such as paraquat, have been associated with an increased risk of Parkinson's disease, and atrazine has demonstrated teratogenic effects, disrupting sex differentiation in frogs during metamorphosis.

(iii) Nematicides are chemical or biological agents used to control or repel nematodes-microscopic, worm-like parasites that damage crops and reduce yields. Chemical nematicides like Aldirab, an acetylcholine esterase inhibitor, are often applied to manage nematode infestations in crops such as tobacco. For example, "Meloidogyne incognita," a common nematode species, attacks tobacco roots, leading to severe yield losses. Biological control agents (BCAs) are also effective; "*Purpureocillium lilacinum*" targets "*M. incognita*" by releasing proteases and chitinase, enzymes that weaken the nematode eggshell to facilitate infection. Another potential BCA, fungi from the genus "*Paecilomyces*," are also promising in nematode control. Other nematicides, such as methyl bromide (MB), ethylene dibromide (EDB), and chloropicrin, are widely used, though their application is sometimes restricted due to environmental concerns. Soil steam sterilization (SSS), which uses heat to inactivate pathogens and nematodes in soil, provides a non-chemical control method by disrupting enzyme function in harmful organisms.

(iv) Rodenticides, commonly known as rat poisons, are substances formulated to control rodent populations. Examples include sodium fluoroacetate, warfarin, red squill, and zinc phosphide. Many of these agents function by disrupting the

Vitamin K cycle in rodents and other mammals, which prevents blood clotting and leads to fatal internal bleeding. Additionally, rodenticides like Vitamin D3, D2, and D1 can cause hypercalcemia (excessively high blood calcium levels) in rodents, leading to severe tissue damage and death. Strychnine, derived from the "Strychnos nux-vomica" tree, is a neurotoxin that causes asphyxiation by inducing muscle spasms. Chloralose, a chlorinated derivative of glucose, is used for controlling rodents and some bird species. Arsenic trioxide combined with copper acetate forms Paris Green, a multipurpose substance used as both a rodenticide and a blue colorant in fireworks.

(v) Insecticides are agents used to control or eliminate insect pests and can be grouped according to their mode of action. Stomach or alimentary canal poisons are ingested by insects, causing toxicity within their digestive systems; examples include azadirachtin from the neem tree (*Azadirachta indica*) and rotenone from the derris plant (*Derris elliptica*). Contact poisons, on the other hand, are lethal upon direct contact with the insect's body, disrupting either the nervous system or the development of the exoskeleton. Pyrethrum, derived from chrysanthemum flowers, and synthetic pyrethroids, which mimic pyrethrum's effects, are well-known contact insecticides.

Fumigants, another type of insecticide, function as gases or vapors that kill insects through inhalation. Commonly used in the treatment of stored grains and enclosed spaces, examples of fumigants include ethylene dibromide (EDB) and methyl bromide.

Insecticides also differ by origin. Natural insecticides, which are extracted from plants or other natural sources, are often seen as environmentally friendlier but may be less potent than synthetic alternatives. Examples of natural insecticides include azadirachtin, rotenone, and pyrethrum. Synthetic insecticides, such as organochlorines, organophosphates, carbamates, pyrethroids, triazines, cypermethrin, insect growth regulators (IGRs), azadirachtin, and hydroprene, are generally more powerful and effective, though they can pose higher risks to human health and the environment due to their persistence and toxicity (Fig. 2).

7 Advantages of Pesticide

Pesticides offer both immediate and long-lasting benefits. Primary benefits, such as the elimination of crop-damaging insects, are directly observable following pesticide application. Secondary benefits, which emerge from these primary effects, persist for extended periods (Mahmood et al., 2015). Pesticide use has garnered significant attention from various stakeholders, including farmers, scientists, governments, and agro-industries (Abubakar et al., 2020).

(i) Pesticides have been hailed as an effective tool in managing agricultural pests, leading to increased crop production. The application of pesticides has

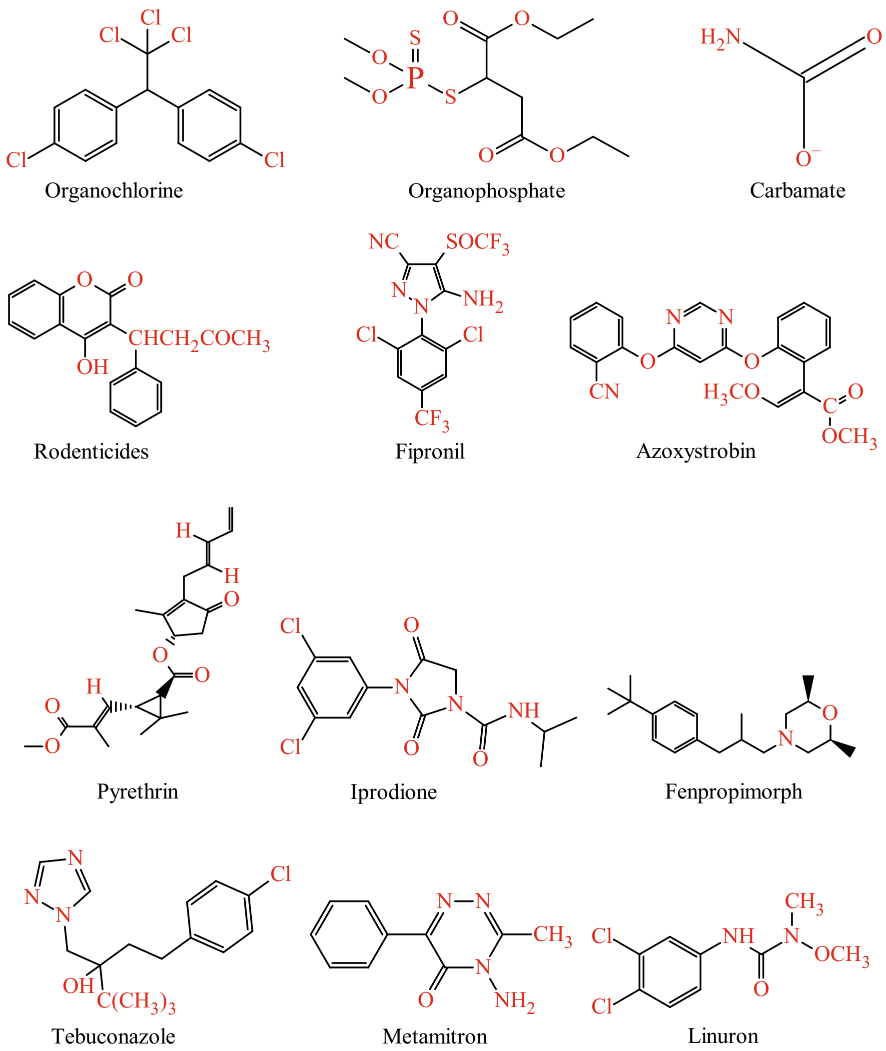
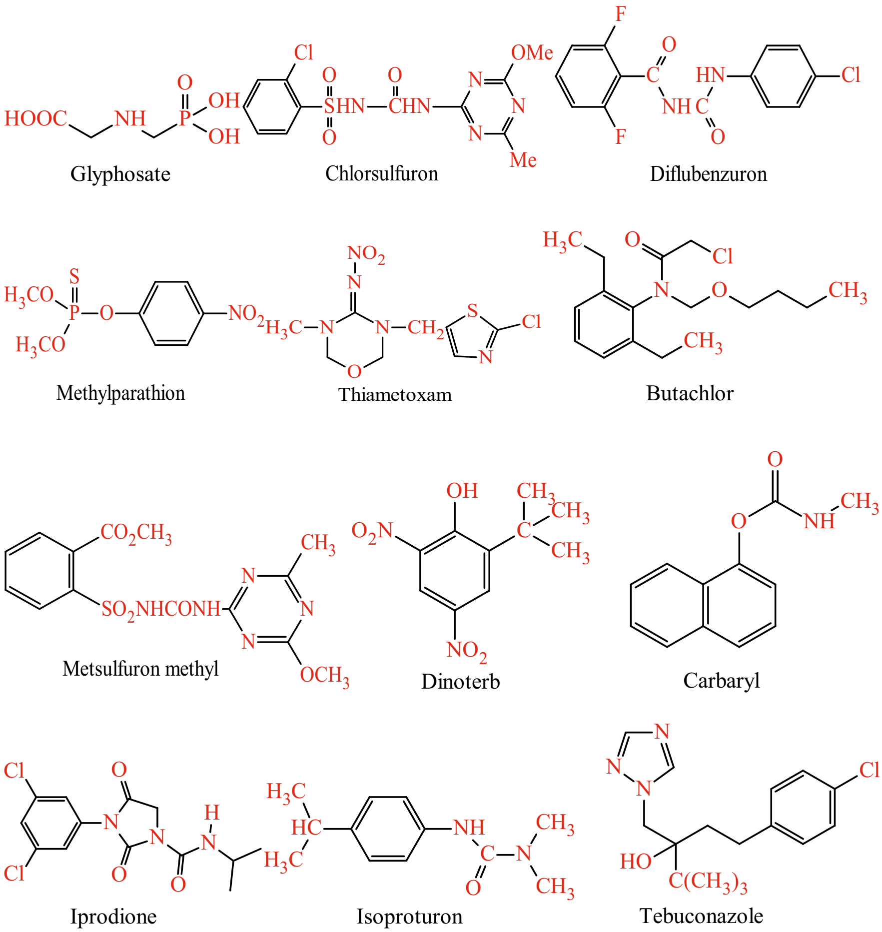


Fig. 2 2D Structure of some common pesticides such as insecticides, fungicides, and herbicide



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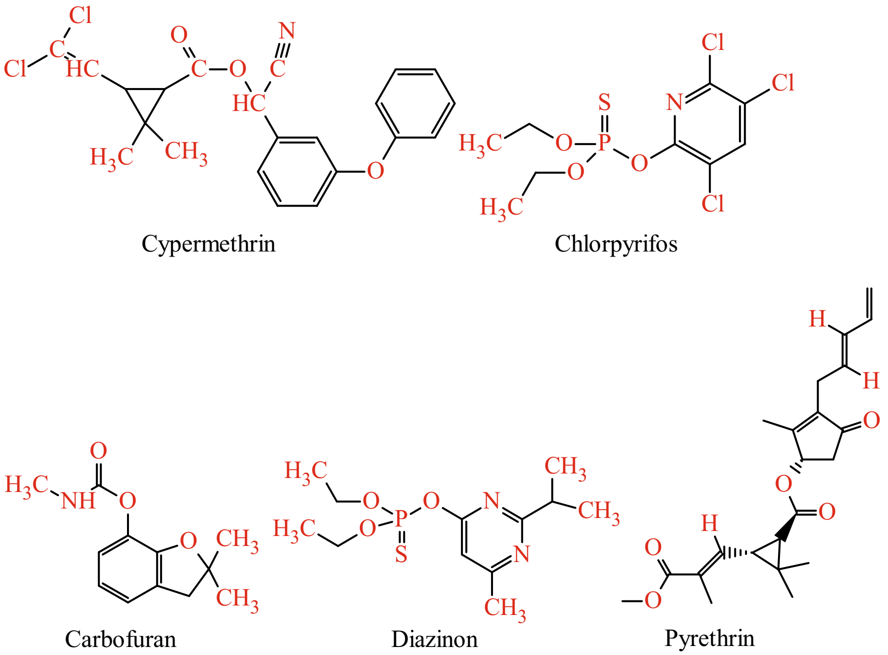
dramatically reduced insect infestations, diseases, and weeds, which can significantly diminish harvestable crop yields and economic returns.

(ii) Pesticide use has contributed to enhanced agricultural production of high-quality food. For instance, the consumption of diets rich in fruits and vegetables outweighs the potential risks associated with consuming low pesticide residues that may remain in some agricultural crops after pesticide application (Pesticide Action Network (Group), 2010).

(iii) Pesticides play a crucial role in preserving wood from destruction by termites and other wood-boring insects. Additionally, they help control the spread of malaria vectors, such as Anopheles mosquitoes (Ross, 2005).

(iv) The adoption of pesticides by farmers for agricultural pest management has motivated scientists and researchers to dedicate significant effort to further



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research and development in the pesticide sector. This has led to the discovery of new types of pesticides with diverse modes of action.

8 Disadvantages of Pesticides

(i) The rampant use of pesticides has led to widespread environmental contamination, posing a significant threat to the quality of soil, water, and air. This contamination can have both short-term and long-term consequences, including the contamination of groundwater and drinking water. The accumulation of pesticide residues in non-target organisms, as observed by Struik and Bonciarelli (1997), further exacerbates the environmental impact (Struik & Bonciarelli, 1997).

(ii) Numerous studies have demonstrated the detrimental effects of pesticides on non-target organisms, including beneficial microorganisms, soil quality, soil enzymes, aquatic microorganisms, and algae (Struik & Bonciarelli, 1997). These unintended consequences disrupt the delicate balance of ecosystems and contribute to environmental degradation.

(iii) The continuous reliance on pesticides has led to the development of resistance in target organisms, as well as cross-resistance to other pesticide components. This resistance necessitates the development of more potent pesticides, perpetuating a vicious cycle of increased pesticide use and exacerbated resistance.
(iv) The overreliance on pesticides has discouraged farmers from exploring alternative pest management strategies, such as natural and organic agricultural practices and the use of biopesticides (Zadoks & Waibel, 2000). A broader approach to pest control is essential for reducing the reliance on pesticides and promoting sustainable agricultural practices.
(v) The indiscriminate use of pesticides poses significant health risks, particularly during post-harvest storage of agricultural crops. Exposure to pesticides, such as Gamalin 20 and Malathion, can lead to a range of health problems, including acute and chronic poisoning, neurobehavioral effects, developmental and reproductive disorders, carcinogenic effects, and immunological effects (Casida & Durkin, 2013). The inadequate washing of pesticide-treated produce before consumption, particularly in developing countries, leads to the ingestion of pesticide residues, contributing to food poisoning and even fatalities. Additionally, studies have linked pesticide exposure to increased infertility and birth defects (Smith & Smith, 2014).
(vi) The pervasive use of pesticides has exacerbated environmental pollution, with pesticide applications significantly contributing to the contamination of soil, water, and air. This contamination poses a serious threat to human health, ecosystem health, and the overall quality of the environment.

9 Toxic Effect of Pesticides Pollution to Plant and Animal

(i) *Pesticide Toxicity to Microorganisms*: Pesticides, employed for pest control on plants and soil, inevitably enter the soil environment through direct application and plant residue incorporation. Within the soil matrix, pesticides undergo a range of physical, chemical, and biological transformations. Some of the resulting chemical products exhibit significant toxicity to soil-dwelling microorganisms (Stanley & Preetha, 2016). Numerous studies have documented the detrimental effects of insecticides on soil microbial properties, including alterations in enzymatic activities. For instance, buprofezin has been shown to adversely impact invertase activity in soil (Hashimi et al., 2020).
(ii) *Pesticide Toxicity to Plants*: Herbicides, while targeting specific plant species, can also inadvertently affect non-target plant life. Non-target plant exposure to herbicides can occur through direct spraying, droplet drift, vapor movement, runoff, leaching, erosion, and improper disposal practices (Hashimi et al., 2020; Marshall & Marshall, 2001). These toxicants pose a significant threat to plant biodiversity (Isenring, 2010).

(iii) *Pesticide Toxicity to Animals*: The widespread dispersion of pesticide residues in the environment has led to substantial mortality among non-target organisms, including bees, birds, amphibians, fish, and small mammals (Carvalho, 2017). Pesticides have also been implicated in population declines of marine mammals, alligators, fish-eating birds, and other animal species. A notable example is the association between the accumulation of persistent chlorinated hydrocarbons, such as DDT, polychlorinated biphenyls (PCBs), and dioxins, in the food chain and the deaths of thousands of Arctic seals.

(iv) *Pesticide Toxicity to Pollinators*: Pollinators play a crucial role in maintaining ecosystem health. Cross-pollinated and self-incompatible plants rely on pollination services for seed production and biodiversity conservation. Honeybees, in particular, are not only nectar collectors but also essential pollinators. Pollen grains adhere to specialized hairs on the bodies of bees, enabling the transfer of pollen between flowers as bees move from plant to plant (Hashimi et al., 2020; Martin, 2015). Approximately 84% of commercially cultivated crops require insect pollination, underscoring the immense value of pollinating insects (Stanley & Preetha, 2016). Globally, honeybees contribute over $200 billion in pollination services annually, playing a vital role in the production of two-thirds of global crops and different wild flowering plants. Honey production is a significant economic activity and a valuable source of food worldwide (Hashimi et al., 2020).

10 Improper Disposal of Pesticides and Human Exposure

Improper disposal of pesticides presents a critical environmental hazard, contaminating soil, water, and air, and threatening both human health and natural ecosystems. Farmers in various global regions have reported discarding unused pesticides on land, often due to limited awareness and inadequate waste management systems in rural areas. This practice results in pesticide buildup in soil and water, disrupting ecosystems and harming unintended organisms (Stanley & Preetha, 2016). In addition to direct pesticide disposal, improper handling of pesticide containers exacerbates the problem. Discarded containers left in fields can leak residual pesticides into the environment, and repurposing empty containers for household storage creates risks of accidental exposure (Isenring, 2010). Burning or burying containers further pollutes the soil, water, and air, releasing toxic residues.

Human exposure to pesticides commonly occurs through contaminated food and water or by inhaling pesticide-contaminated air, with pesticides entering the body via ingestion, inhalation, or skin contact. International organizations, including the World Health Organization (WHO), the United States Food and Drug Administration (USFDA), and the Food and Agriculture Organization of the United Nations (FAO), have implemented regulatory frameworks to reduce human exposure. These include setting maximum residue limits (MRLs) for pesticides in food products, taking into account that pesticide effectiveness can be influenced by factors like wind speed and humidity (Davis et al., 2008; Fenik et al., 2011).

Pesticide exposure occurs through two main pathways: occupational and non-occupational. Occupational exposure primarily affects individuals involved in pesticide production, application, or disposal, while non-occupational exposure impacts the general population through contaminated food, water, or air (Davis et al., 2008; Hoh & Hites, 2004; Sharma et al., 2019).

11 Environmental Effect of Pesticides Pollution

Globally, an estimated 40% of agricultural produce is lost each year due to plant diseases, weeds, and pests. Without pesticide use, crop losses would likely increase significantly. These crop-protecting substances not only prevent damage but also improve yields (Aktar et al., 2009; Bajwa et al., 2017; Ross, 2005). Failing to protect crops from pests could reduce production, leading to food shortages and increased food prices, so pesticides indirectly contribute to food price stability. Many crops are also prone to aflatoxin contamination, requiring insect control to prevent the transfer of these carcinogenic toxins from insects to plants. Aflatoxins, known to cause liver and other cancers, can impair immune function and stunt growth in children. Pesticides are often used to reduce aflatoxin contamination by targeting insects responsible for its spread (Boutsalis et al., 2012; Ross, 2005).

The effects of pesticides on populations depend on exposure levels, toxicity, species characteristics, timing, population dynamics, and landscape factors (Schmolke et al., 2010). Some insecticides work by targeting insect nervous systems, such as organophosphates and methyl-carbamates, which inhibit acetylcholinesterase; neonicotinoids, which act on nicotinic acetylcholine receptors; and pyrethroids and DDT, which target sodium channels (Casida & Durkin, 2013). Neonicotinoid use, in particular, is on the rise and has raised concerns about toxicity (van Dijk, 2010). However, the overuse of pesticides poses risks to human health and biodiversity, and their water solubility, stability, and polar properties make it difficult to control their impact on the environment (Agrawal et al., 2010). Pesticides can induce toxicity not only in agriculture but also in industrial and public health sectors, harming the environment, natural flora, fauna, and aquatic ecosystems (Schmolke et al., 2010).

12 Health Effect of Pesticides Pollution

Pesticides have played a critical role in advancing public health by controlling vector-borne diseases. However, their extensive and often indiscriminate use has led to growing concerns about long-term health effects. Infants and young children are particularly vulnerable to pesticide exposure due to the non-specific nature of these chemicals and improper application practices. The surge in pesticide use over the past few decades has increased human exposure, especially in developing countries where the World Health Organization estimates around three million pesticide poisoning cases and 220,000 deaths occur each year (Kaur et al., 2019). Additionally, approximately 2.2 million people, mainly in these regions, are at heightened risk of pesticide exposure (Agrawal et al., 2010).

Certain groups, including young children, agricultural workers, and pesticide applicators, face a higher risk of toxic exposure (Abong'o et al., 2014; Ahmad et al., 2024). Pesticides can enter the human body through ingestion, inhalation, or skin absorption, leading to both acute and chronic health impacts (Pozo et al., 2011), with contaminated food being the primary exposure source. After ingestion, pesticides can cross various biological barriers before reaching tissues or storage sites (van der Werf, 1996). While the human body has detoxification mechanisms, excessive exposure can cause these chemicals to accumulate in the circulatory system, reaching toxic levels (Jabbar & Mallick, 1994). Studies have shown links between cancer risks and certain pesticide residues found in foods like fish (Kaur et al., 2019), water (Buczyńska & Szadkowska-Stańczyk, 2005), seafood (Moon et al., 2009), and dairy products (Pesticide Action Network, 2010). While cancer associations have been noted for specific residues, such as DDT and DDD, no significant link has been established for some other organochlorines, though PCBs (polychlorinated biphenyls) have been found to pose a notable risk (Kaur et al., 2019).

13 Acute Effect of Pesticides on Human Health

Direct exposure to pesticides can trigger a range of immediate health effects, ranging from mild irritation to severe life-threatening conditions. These acute effects can manifest through various routes of exposure, including inhalation, ingestion, dermal contact, and ocular exposure.

Common symptoms associated with acute pesticide exposure include:

- Eye irritation: Stinging, burning, redness, and blurred vision
- Skin irritation: Itching, rashes, blisters, and discomfort
- Respiratory irritation: Coughing, wheezing, shortness of breath, and chest tightness
- Gastrointestinal distress: Nausea, vomiting, abdominal cramps, and diarrhea
- Neurological disturbances: Headache, dizziness, fatigue, and tremors

In severe cases, acute pesticide exposure can lead to more serious health complications, including seizures, convulsions, loss of consciousness, respiratory failure, and death. The severity of acute pesticide poisoning depends on various factors, including the type of pesticide, the amount of exposure, the individual's sensitivity, and the route of exposure (Abong'o et al., 2014; Ahmad et al., 2024; van Dijk, 2010; Hashimi et al., 2020; Moon et al., 2009).

14 Chronic Effect of Pesticides on Human Health

Chronic pesticide exposure poses a serious, often overlooked risk to human health, with adverse effects that may take years to surface. Long-term contact with these toxic substances can disrupt multiple organ systems, leading to a host of serious health problems. Neurological impairment, immune system disruption, heightened cancer risk, reproductive issues, and organ damage are just some of the potential outcomes. Recent studies indicate a possible link between chronic exposure to pesticides and a higher likelihood of developing neurodegenerative conditions like Parkinson's and Alzheimer's diseases (Buczyńska & Szadkowska-Stańczyk, 2005; Moon et al., 2009; Pesticide Action Network, 2010; Rola & Pingali, 1993).

15 Distribution of Pesticides Consumption and Usage Worldwide

A sustained rise in global agricultural pesticide consumption was observed from 1990 to 2021, reaching nearly 3.54 million metric tons in the latter year. This upward trend is likely attributable to the burgeoning demand for crop protection chemicals, driven by the concurrent challenges of climate change, evolving pest resistance, and a growing population. Notably, the Americas held the dominant position in 2021, accounting for over half of global agricultural pesticide use. Asia and Europe followed with considerably lower shares of 27.7% and 14.3%, respectively. In contrast, Africa and Oceania collectively consumed less than 8% of the world's total (Global Pesticide Consumption 1990–2021, n.d.; Pesticide Action Network (Group), 2010; Zhang et al., 2011).

16 Pesticides Usage Worldwide and Their Effect

16.1 The Use of Pesticides in Africa and Its Associated Risks

Agriculture is essential to the African economy, with approximately 59% of the population dependent on farming. Despite this reliance, Africa represents only 2–4% of the global pesticide market and has the world's lowest pesticide usage rate (Abate et al., 2000). However, rising population pressures and food demand are expected to increase pesticide, herbicide, and fungicide use over the next three decades (Snyder et al., 2015). To maintain high yields and profitability, many African farmers are increasingly dependent on pesticides (de Bon et al., 2014).

Government policies have further shaped pesticide use trends. Since the 1970s, many African governments promoted pesticide use, but policy changes in the 1990s reduced input subsidies, leading to less government oversight and a sharp rise in pesticide imports through informal channels. Between 2000 and 2010, the import value of pesticides surged by 261%, largely due to unregulated imports (de Bon et al., 2014).

This lack of regulation has allowed banned pesticides to enter African markets. Inadequate farmer awareness has led to improper pesticide use, and non-compliance with Food and Agriculture Organization (FAO) codes of conduct has resulted in untested, potentially dangerous pesticide applications. Many farmers unknowingly use hazardous pesticides classified under the World Health Organization (WHO) risk system. For instance, the Pesticide Risk Reduction Program (PRRP) in Ethiopia found that 160 of 302 registered pesticides contain WHO class II (moderately hazardous) chemicals (Khan et al., 2010; Joseph Shaba et al., 2019; Kaur et al., 2019). Studies from Botswana, Nigeria, Zambia, and Malawi similarly reveal high usage of WHO-classified hazardous pesticides, including Malathion, cypermethrin, methomyl, and monocrotophos (Obopile et al., 2008; Oluwole & Cheke, 2009; Nyirenda et al., 2011).

Pesticide use in Africa also raises concerns about pest resistance, which threatens crop yields despite pesticide application. For example, pyrethroid resistance has emerged in tomato bollworm (*Heliothis armigera*) and diamondback moth (*Plutella xylostella*) in West Africa (de Bon et al., 2014; Martin, 2015). Resistance in the aphid *Aphis gossypii* to pyrethroids and organophosphates, and in the whitefly *Bemisia tabaci* to multiple pesticide classes, highlights the need for sustainable pest management practices (Carletto et al., 2010; Houndété et al., 2010).

16.2 The Use of Pesticides in Asia and Its Associated Risks

The use of pesticides in agricultural practices has significantly increased in developing countries, particularly in Southeast Asia. According to the World Health Organization (WHO), approximately 20% of global pesticide consumption occurs in these regions. Countries like Cambodia, Laos, and Vietnam have experienced notable annual increases in pesticide imports, with rates of 61%, 55%, and 10%, respectively (Schreinemachers & Tipraqsa, 2012).

In India, pesticide manufacturing began in 1952 with the production of benzene hexachloride, followed by DDT. The industry expanded rapidly, with India producing over 5000 metric tons of pesticides in 1958, reaching 85,000 metric tons by the mid-1990s. By this time, 145 pesticides had been registered, with insecticides being the dominant category (Ahad et al., 2010; Khan et al., 2010).

Similarly, Pakistan's pesticide usage began in 1954, initially importing 250 metric tons (Jabbar & Mallick, 1994). By 2003, annual pesticide consumption in Pakistan had risen dramatically to 78,132 tons (Pozo et al., 2011; Syed & Malik, 2011). During the Green Revolution, Pakistan significantly increased its pesticide imports from Europe and the United States to address pest infestations, control locust outbreaks, and suppress malaria (Ahad et al., 2010).

This surge in pesticide usage across Southeast Asia and South Asia highlights the growing reliance on chemicals to sustain agricultural production, although it also raises concerns regarding environmental and health risks associated with their widespread application.

16.3 The Use of Pesticides in Australia and Its Associated Risks

Australian farmers have shown a willingness to incur higher chemical costs to effectively manage pest infestations, with the agricultural pesticide market valued at A$187 million annually (Llewellyn et al., 2016). This includes herbicides, insecticides, fungicides, and certain growth regulators. The costs of herbicides, in particular, have risen due to the use of alternative herbicides, mixtures, and higher concentration rates, which add approximately A$8 per hectare.

Weed infestations significantly reduce crop productivity and quality, making effective weed control essential for maintaining agricultural productivity. Herbicide application is an effective method for managing weeds, thus making it an attractive choice for farmers. However, concerns arise from the overuse of herbicides, especially those with similar modes of action, which can lead to the development of herbicide-resistant biotypes. This resistance, which has been observed in several weed species, poses a long-term challenge for sustainable agricultural practices and highlights the need for integrated pest management strategies to mitigate resistance development (Walsh & Powles, 2014).

16.4 The Use of Pesticides in Europe and Its Associated Risks

The widespread use of insecticides, herbicides, fungicides, and chemical fertilizers across Europe has contributed to increasing pest infestations in agricultural lands, which, in turn, has caused a decline in natural habitats and reduced the heterogeneity of farmlands and surrounding landscapes (Miraglia et al., 2009; Struik & Bonciarelli, 1997). A joint survey across seven European countries, including Latvia, Denmark, Germany, the Netherlands, Finland, Sweden, and the UK, highlighted the growing use of pesticides in both urban and non-agricultural areas (Walsh & Powles, 2014). Herbicides were identified as the main pesticide contaminants in urban environments, with significant regional variations in political interest, public discourse, and regulations on pesticide use in urban settings.

Countries like Denmark, the Netherlands, Germany, and Sweden have shown strong political and public interest in reducing herbicide use for urban weed control. In contrast, while the UK has implemented stricter regulations, Finland and Latvia still lack specific measures to curb pesticide use. Finland, in particular, has experienced a rise in pesticide use, though it remains relatively low compared to other European regions, with annual pesticide consumption estimated at 5–6 metric tons (Zhang et al., 2011). A 2007 survey of 80 Finnish municipalities revealed that while one-fifth occasionally used pesticides, only about 15% reported regular use.

Additionally, a study in Greece detected pesticides in hot spring water samples, though none exceeded the European Union's Maximum Acceptable Concentration (MAC). Lindane (γ-BHC), a commonly used pesticide, was found in 35% of the samples, with concentrations ranging from 0.005 to 0.01 μg/L, further illustrating the pervasive presence of pesticides in the environment (Sharma et al., 2019).

17 Impacts of Pesticide Pollution and Contamination on Global Ecosystem

The widespread and excessive use of pesticides has raised significant environmental concerns, particularly regarding their safe storage, disposal, and their impact on ecosystems. Pesticide misuse has been linked to soil and water contamination, which adversely affects the delicate balance of soil microflora and microfauna and impairs plants' ability to absorb essential nutrients (van der Werf, 1996). Pesticide leaching exacerbates the problem by contaminating local water bodies, with groundwater contamination posing a serious threat to drinking water supplies (Sharma et al., 2019).

In Australia, pesticide runoff from agricultural lands, especially in the Tasmanian forestry industry, has raised alarms due to its impact on coastal and inshore ecosystems, including the Great Barrier Reef (GBR). The extensive use of triazine herbicides has left residual contamination in agricultural catchments, which affects marine organisms such as seagrass, corals, and algae (Barzman et al., 2015). Herbicides like atrazine and diuron are commonly found in GBR sediments, with seasonal pesticide movement detected in the agricultural floodplains of the lower Burdekin River. The majority of detected pesticides were linked to the sugarcane industry, with runoff being a major contributor to water contamination (Davis et al., 2008).

This contamination, resulting from agricultural waste discharge and runoff, enters the food chain and poses risks to aquatic life. Fish consuming contaminated water may become unsafe for human consumption. In Central America and other regions, the continuous use of pesticides has led to elevated concentrations of hazardous chemicals like DDT, chlordane, p,p′-DDE, and toxaphene in the air (Hoh & Hites, 2004). In South America, pesticides such as chlorpyrifos, endosulfan, and cypermethrin have frequently been detected in water bodies, indicating the ongoing challenge of pesticide pollution in the environment (Ahad et al., 2010; Syed & Malik, 2011). These persistent chemicals threaten not only wildlife but also human health through the contamination of water resources and the food chain.

18 Threats of Pesticide Pollution to Biodiversity

The indiscriminate use of pesticides presents a serious threat to biodiversity, necessitating urgent attention and comprehensive mitigation strategies. Pesticides have far-reaching effects on both aquatic and terrestrial ecosystems, impacting a wide variety of organisms, including plants, animals, and birds. A particularly concerning aspect is the bioaccumulation of pesticides within the food chain, which leads to harmful consequences for predator and raptor populations. Studies have shown that pesticides, when ingested by lower-level organisms, gradually accumulate in the tissues of higher-level predators, affecting their health and reproductive capabilities (van Dijk, 2010; Hashimi et al., 2020; Mahmood et al., 2015).

Furthermore, the widespread application of pesticides can indirectly reduce the abundance of weeds, shrubs, and insects, which are crucial food sources for many species. The loss of these essential food resources can cause declines in the populations of various animals and birds, some of which may be rare or endangered. The indiscriminate spraying of insecticides, herbicides, and fungicides has been linked to a significant decrease in the numbers of certain species, with some experiencing population crashes due to the direct and indirect effects of pesticide exposure. The long-term and frequent use of pesticides exacerbates the issue of bioaccumulation, causing further ecological damage over time (Isenring, 2010; Marshall, 2001).

In addition to harming individual species, the disruption of food webs and ecosystems can lead to cascading effects, undermining ecosystem services that are vital for maintaining biodiversity. These changes can also make ecosystems less resilient to other environmental stresses, such as climate change and habitat loss, creating a feedback loop of ecological degradation. As such, it is crucial to adopt more sustainable agricultural practices and regulations that limit the use of harmful pesticides, promote alternatives, and prioritize ecological balance.

19 Climate Change and Its Impact on Pesticides Pollution and Food Systems

Climate change has become a central issue in the global food system, with far-reaching effects on agricultural production. Rising temperatures, altered rainfall patterns, increased drought frequency, and disrupted seasonal variations all contribute to significant changes in crop yields. Additionally, elevated CO_2 levels and changes in soil quality, as well as the forced relocation of cropping systems due to water scarcity, further exacerbate these challenges (Bailey, 2004; Miraglia et al., 2009; Muriel et al., 2000). These shifts make crops more susceptible to plant diseases and insect infestations, increasing the reliance on pesticides for protection.

The direct impacts of climate change on pesticide efficacy are complex. Water scarcity and degradation due to high atmospheric temperatures reduce soil bioactivity, while elevated temperatures often lead to a reduction in soil organic matter. This can result in greater root uptake of pesticides that would otherwise be bound to the soil's organic matter. Furthermore, higher temperatures may cause pesticides to evaporate more quickly, reducing their effectiveness (Miraglia et al., 2009). In arid conditions, many pesticides are less effective, requiring higher doses or more frequent applications to ensure adequate crop protection (Muriel et al., 2000). Some studies suggest that climate change may also accelerate the degradation of certain pesticides under extreme temperatures, further complicating their use (Bailey, 2004). These effects contribute to food security concerns, as the efficacy and application of pesticides become increasingly unpredictable in the face of climate change.

To address the growing concerns about pesticide use, the concept of "Integrated Pest Management (IPM)" has emerged as a sustainable approach to crop protection. IPM, which began in 1959 as a strategy to control the spotted alfalfa aphid in the United States, integrates various pest management methods based on cost–benefit analysis. It aims to reduce reliance on synthetic pesticides while promoting sustainable agriculture (Kogan, 1998; Stern et al., 1959). The European Union has actively supported the adoption of IPM through the enactment of the "Sustainable Use of Pesticides" Directive (2009/128/EC), which encourages Member States to develop National Action Plans to reduce pesticide use.

IPM programs focus on minimizing pesticide use, enhancing biodiversity, and increasing resilience to pests and diseases. The EU directive promotes the inclusion of IPM as a core component of national pesticide management programs. These initiatives are complemented by measures such as pest forecasting, pesticide resistance monitoring, and training programs for farmers to ensure that IPM strategies are effectively implemented (Pimentel, 2005; Barzman et al., 2015). Globally, the adoption of IPM principles is growing, with farmer field schools engaging millions of farmers in sustainable pest management practices since 1989 (Sharma et al., 2019). This shift toward more sustainable agricultural practices reflects the increasing recognition of the need for systems that reduce pesticide dependency while maintaining food security.

20 Pesticide Legislation and Regulatory Frameworks: A Global Perspective

Pesticide legislation and management practices differ significantly across countries due to various socioeconomic, environmental, and regulatory contexts. The management of pesticides throughout their lifecycle ranging from manufacturing and application to risk reduction, monitoring, and waste disposal requires a multifaceted approach that is often more robust in developed countries compared to developing nations. In many developed countries, stringent pesticide regulations have been implemented, often supported by comprehensive legal frameworks, monitoring programs, and infrastructure. Conversely, developing countries face several challenges, including inadequate legislation, resource constraints, lack of expertise, and insufficient infrastructure for pesticide analysis. These factors contribute to difficulties in enforcing pesticide regulations and managing associated risks effectively (Handford et al., 2015).

A key international organization involved in pesticide management is the Codex Alimentarius Commission (CAC), a joint initiative of the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO). The CAC has established standards for pesticide residues in food commodities, offering a global framework to minimize contamination risks and safeguard food safety across the supply chain. However, despite these global standards, a significant gap in pesticide management is the lack of comprehensive guidelines tailored to specific farming systems. Such guidelines would consider the economic, social, and environmental impacts of pesticide use, promoting the production of safe and healthy food through sustainable methods (Leong et al., 2020).

To address the potential health risks posed by pesticides, organizations like the FAO have developed toxicological reference values, such as the Acceptable Daily Intake (ADI) and Acute Reference Dose (ARfD). The ADI represents the amount of a pesticide that can be ingested daily over a lifetime without posing a significant health risk, expressed in milligrams per kilogram of body weight per day. This value is based on scientific data available at the time of evaluation. The European Union (EU) has adopted Maximum Residue Limits (MRLs), which are often more stringent than the standards set by the Codex Alimentarius. The approval process for new pesticides in the EU is rigorous, involving an extensive evaluation by the European Food Safety Authority (EFSA) and EU member states, which can take up to 3 years. Additionally, countries within the EU may establish "national MRLs" to address local dietary patterns and risk profiles, ensuring that pesticide use aligns with regional health and safety needs. Overall, while significant progress has been made in pesticide regulation in developed countries, much work remains to improve pesticide management in developing nations. This includes the need for stronger legal frameworks, better enforcement mechanisms, and more tailored, sustainable approaches to pesticide use that prioritize both public health and environmental protection.

21 Biopesticides: Natural Pesticides an Alternative to Chemical Pesticides

The growing awareness of the detrimental effects of chemical pesticides on human health and the environment has spurred the search for sustainable alternatives. Biopesticides, derived from natural sources such as plants, microbes, and animals, emerged as a promising solution (EU Legislation on MRLs – European Commission, n.d.; Simon et al., 2024). These substances offer a nontoxic approach to pest control, mitigating the environmental and health concerns associated with conventional pesticides. Biopesticides can be broadly classified into two main categories:

biochemical pest control agents and microbial pest control agents. Biochemical agents, including pheromones, hormones, natural plant growth regulators, and enzymes, disrupt the pest's life cycle and reproductive processes without harming non-target organisms. Microbial agents, on the other hand, utilize microorganisms, such as bacteria, fungi, viruses, and protozoa, to directly kill pests or disrupt their development and behavior.

The development of biopesticides with novel modes of action and minimal cross-resistance to conventional pesticides is a subject of ongoing research. Biopesticides offer several advantages over their synthetic counterparts, including:

(i) Environmental Friendliness: Biopesticides are biodegradable and typically have a narrow spectrum of activity, targeting specific pests without harming beneficial organisms or the environment.
(ii) Reduced Human Health Risks: Biopesticides generally exhibit lower toxicity to humans and animals, posing minimal risks to applicators and consumers.
(iii) Organic Production Compatibility: Biopesticides are essential components of certified organic agricultural practices, adhering to strict standards that promote sustainable and environmentally friendly farming methods.
(iv) Reduced Residue Concerns: Biopesticides often have shorter persistence in the environment and leave fewer residues on treated crops, allowing for harvest closer to application.
(v) Rapid Pest Control: Biopesticides can act quickly to disrupt pest feeding, providing immediate relief from pest damage.

Despite their advantages, biopesticides also has various disadvantages such as:

(i) Narrow Spectrum of Activity: Biopesticides often target specific pests, limiting their broad applicability across a range of pests.
(ii) Weather Dependence: Environmental factors, such as temperature, humidity, and sunlight, can affect the efficacy of biopesticides.
(iii) Storage and Shelf Life: Proper storage conditions are crucial to maintain the viability and effectiveness of microbial biopesticides.
(iv) Regulatory Requirements: Extensive testing and registration processes are required to ensure the safety and efficacy of biopesticides before commercialization (Ahmad et al., 2024).

21.1 Types of Natural Pesticides

The realm of natural pesticides encompasses a diverse array of botanicals, microbials, essential oils, and mineral-based agents, many of which are derived from plants, insects, or naturally occurring minerals. These natural alternatives offer a compelling solution to the growing concerns associated with conventional pesticides, which often pose significant risks to human health and the environment. Examples are:

(i) Microbial pesticides, encompassing fungi, bacteria, protozoans, algae, and viruses, exploit the inherent pathogenicity of microorganisms to combat insect populations. Genetically engineered variants further enhance the efficacy of these biopesticides, targeting specific insects with increased potency. The mode of action of microbial pesticides varies, encompassing disease induction, toxin production, and reproductive inhibition. *Bacillus thuringiensis*, commonly known as milky spore, exemplifies a microbial pesticide that disrupts insect development.

(ii) Mineral-based pesticides, such as sulfur and lime-sulfur, have long been employed in pest control strategies. These compounds are typically applied as sprays to combat common insect pests.

(iii) Botanical pesticides harness the insecticidal properties of various plants. Nicotine, neem, rotenone, anabasine, azadirachtin, ryania, essential oils, sabadilla, and pyrethrins are all derived from plant sources. Pyrethrins, extracted from chrysanthemum plants, are particularly effective against flying insects, larvae, and grubs. Botanical pesticides can be classified as constitutive chemicals, naturally present in the plant, or inducible chemicals, activated in response to insect activity. Some botanical pesticides undergo chemical modifications after extraction to enhance their insecticidal properties (Joseph Shaba et al., 2019).

22 Conclusion

The widespread adoption of pesticides in modern agriculture has indeed transformed food production, allowing for higher crop yields and more affordable food prices. This increase in agricultural productivity has significantly contributed to global food security, making nutrient-rich food more accessible to larger populations. Without pesticides, achieving such a feat would have been much more challenging, especially in terms of controlling pests and diseases that could otherwise decimate crops. However, this agricultural success has come with a substantial environmental and health cost. The indiscriminate use of pesticides, often motivated by the pursuit of immediate results and economic affordability, has resulted in widespread environmental contamination. Toxic residues from pesticides persist in the environment, accumulating in soil, water, and air. These chemicals can disrupt ecosystems and harm non-target organisms, including beneficial insects, wildlife, and aquatic life. For example, pesticides can harm pollinators like bees, which are essential for the reproduction of many plants. Moreover, pesticides can lead to the development of resistance in pest populations, prompting the need for even more toxic chemicals, creating a vicious cycle of pesticide use and environmental degradation.

The harmful effects of pesticides also extend to human health. Exposure to these chemicals can lead to a range of health issues, particularly when individuals are exposed to high concentrations or over long periods. Children, pregnant women, and developing organisms are especially vulnerable. Health problems associated with pesticide exposure include neurological disorders, respiratory issues, and an increased risk of cancers and reproductive disorders. Though many harmful pesticides have been banned or restricted in developed countries, they are still widely used in many developing nations where they are seen as cost-effective and efficient solutions for pest control. This continued use in developing regions poses significant health risks to agricultural workers and surrounding communities.

In light of the growing concerns regarding the negative impacts of synthetic pesticides, biopesticides which are pesticides derived from natural sources like plants, microbes, and animals have emerged as a promising alternative. Biopesticides are generally more specific in their action, targeting particular pests without affecting beneficial organisms or the broader ecosystem. They typically break down more quickly in the environment, reducing the risk of long-term environmental contamination. Some biopesticides work by disrupting the growth and development of pests, while others can stimulate natural pest resistance in plants or attract predators that control pest populations. As research into biopesticides continues to advance, they hold the potential to significantly reduce the reliance on synthetic pesticides, offering a more sustainable and eco-friendly solution to pest management in agriculture.

Ultimately, the challenge is to find a balance between maintaining high levels of agricultural productivity and minimizing the negative environmental and health impacts of pesticide use. Shifting toward more sustainable and integrated pest management approaches, including the use of biopesticides, could help address many of these challenges while preserving the benefits of modern agriculture.

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