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Towards sustainable agriculture: Balancing pesticides in soil for environmental harmony

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Abstract
Using pesticides has always been an issue in agriculture since we also have to take care of the environment. For a while now, there have been discussions over the use of pesticides in agriculture, which usually clashes with the imperative of sustainable development. Pest control agents, i.e., pesticides, are substances formulated to kill insects-pests that feed on crops, thus destroying the same. These chemicals eliminate pests and reduce their reproduction (Kumar *et al.*, 2019). For centuries, different types of pesticides have been used for crop protection. While pesticides are advantageous to crops, they cause severe environmental consequences and can lead to biodiversity loss. These toxic agents pose a grave danger to animals, birds, soil microorganisms, and aquatic organisms for survival, putting them at risk of extinction (Mahmood *et al.*, 2016). This paper discusses how pesticides affect soil quality and approaches for attaining pest management and sustainability goals. It demonstrates the consequences pesticides have on soil health, the possible dangers for ecosystems, and the possibility of finding a balance between effective pest control and the need for a scientifically oriented strategy for tackling pest control issues. The impact of pesticides on soil quality and possible repercussions for ecosystems are explored in this paper, along with other alternatives for keeping pest pressure under control without damaging the environment and ways of keeping pests within permissible limits.

Keywords: Alternative pest control, ecosystem, pest management, pesticide effects, soil health, sustainability

Introduction

Food is a basic necessity for survival. It provides energy and supplements maintenance, repair, and production for bodybuilding. As the population is increasing rapidly, the agricultural sector faces the challenge of meeting the demand for food while minimizing the environmental impact. Farmers are not getting good yields of their crops as they are greatly affected by damage from several species of insect pests and weeds. In agriculture, pests are damaging in terms of yield and increase the cost of cultivation as billions of dollars are spent on pesticides annually, which increases agricultural generation costs.

Pests are "plants and animals that jeopardize our food, health, and comfort" (Mahmood *et al.*, 2016) [29]. Pest is another term that refers to any living body, whether animals or plants, that endangers human existence or that of other living animals. Pesticides are toxic chemicals, mixed substances, or biological agents deliberately released into the environment to avert, deter, control, kill, and destroy the harmful populations of insects, weeds, rodents, fungi, or other harmful pests (Zhang, 2018) [28]. Pesticides are chemicals whose primary function is to eliminate insects, pests, rodents, fungi, and weeds. They contain insecticides, herbicides, nematicides, fungicides, molluscicides, rodents, plant growth regulators, and other compounds. The Food and Agriculture Organization (FAO) of the United Nations defines a *pesticide* as "any substance or blend of substances planned for avoiding, devastating, or controlling any irritation, including vectors of human or creature ailment, undesirable types of plants or creatures, causing destruction among or generally interfering with the generation, preparing, storage, transport, or promoting of sustenance, horticultural items, wood, and wood items or animal feedstuffs, or substances that might be directed to animals for the control of bugs or different pests in or on their bodies." The use of various pesticides has multiplied several times in the last few decades(Mahmood *et al.*, 2016) [29].

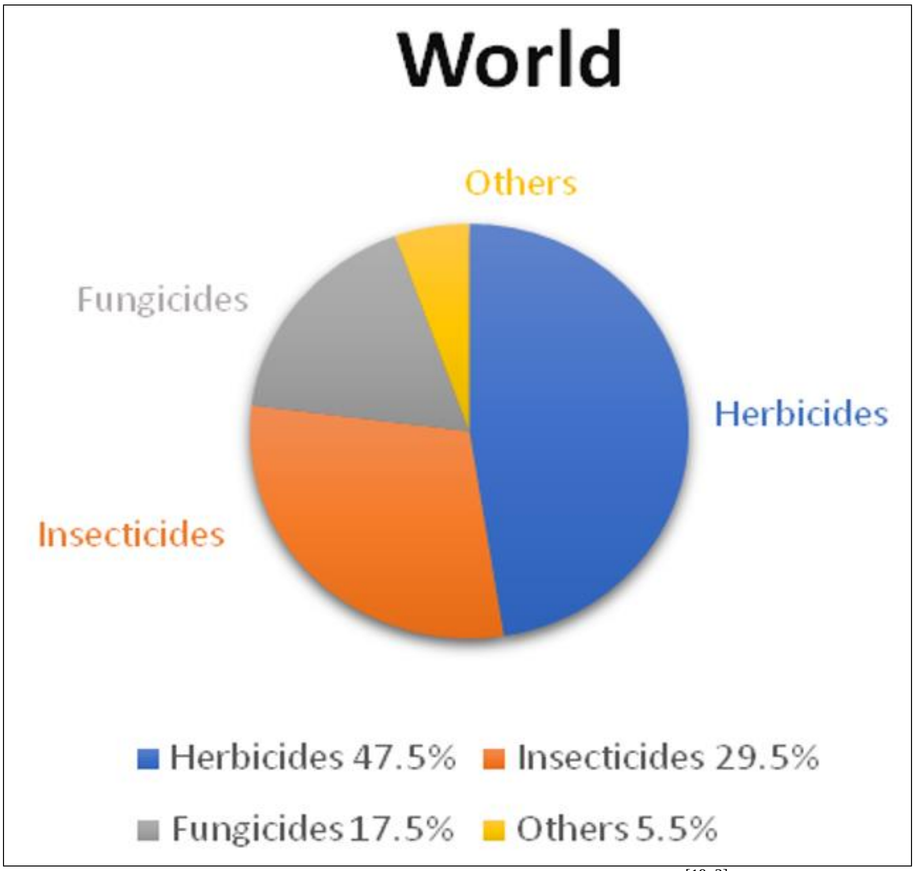
Pesticides are essential in controlling pests, diseases, and weeds, but their application adversely affects soil ecosystems and surrounding environments. These severely affect soil health, environment, birds, animals, and human health. Due to their accumulation in soil and then in food has caused a large number of issues for humans. The author "Rachel Carson" in her book "Silent Spring" termed pesticides "biocides," as the effects are rarely limited to solely targeting pests due to their detrimental effects on the environment, its flora-fauna, and humans (Jabbar and Mallick 1994) [14]. This paper explores the delicate balance between pest control and environmental sustainability. This paper aims to provide an overview of the impact of pesticides on soil health, its flora, and fauna and explore strategies to balance effective pest control with environmental sustainability. It also discusses alternative approaches to reducing reliance on pesticides in agriculture, such as IPM, resistant varieties, genetically modified crops, etc. It focuses on a science-based approach to tackling the challenges associated with pest management.

Pesticide usage patterns

Throughout history, various chemical compounds have been employed to manage pest populations. Notably, sulfur compounds effectively control insects and mites (Gyawali, 2018) [11]. Before the arrival of dichloro diphenyl trichloroethane (DDT) by Paul Herman Muller in 1939, saline water and various chemical compounds, both organic and inorganic, were widely utilized to curb pest populations (Abubakar *et al.*, 2020) [1].

In world

In 2019, global pesticide consumption reached around 4.19 million metric tons, with China being the leading consumer at 1.76 million metric tons, trailed by the United States (408 thousand tons), Brazil (377 thousand tons), and Argentina (204 thousand tons) (Pathak *et al.*, 2022) [20]. Southeast Asia experienced an annual rise in pesticide usage, as reported by the World Health Organization (WHO), with 20% of developing countries in the region being pesticide consumers (Schreinemachers *et al.*, 2015) [24]. From 2010 to 2014, the average cost/benefit ratio was 0.645 grams of total pesticides per kilogram of crop yield, with an average yearly consumption of 2.784 kg ha^{-1}. Japan led in average pesticide usage during this period with 18.94 kg ha^{-1}, followed by China (10.45 kg ha^{-1}) and India (0.26 kg ha^{-1}). Regarding pesticide contributions, herbicides constitute 47.5%, insecticides at 29.5%, fungicides at 17.5%, and other insecticides at 5.5% (Zhang, 2018) [28].

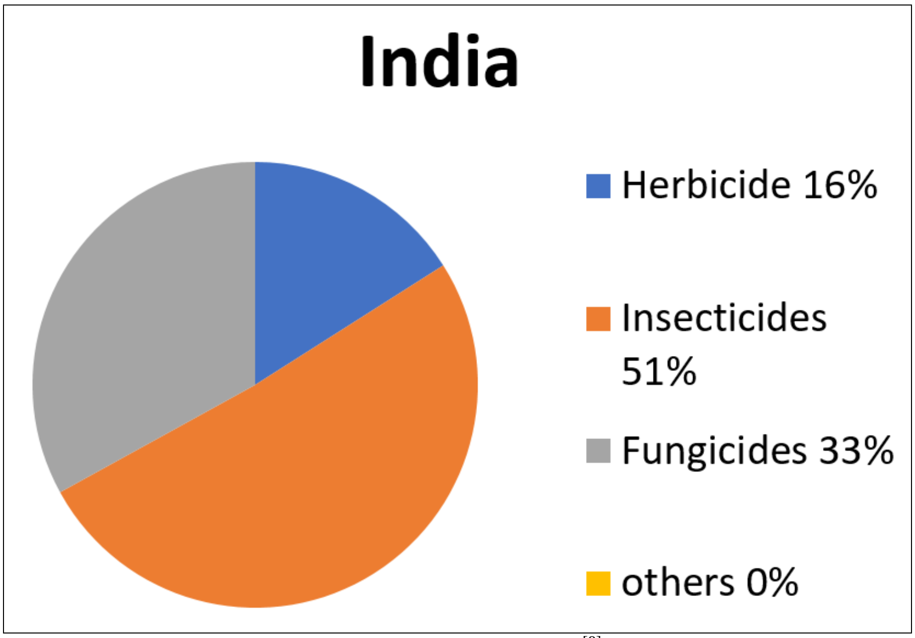


(**Source:** Nicolopoulou-Stamati *et al*., 2016; Alengebawy *et al*., 2021) [19, 3]

Fig 1: Pesticide use pattern world

In India

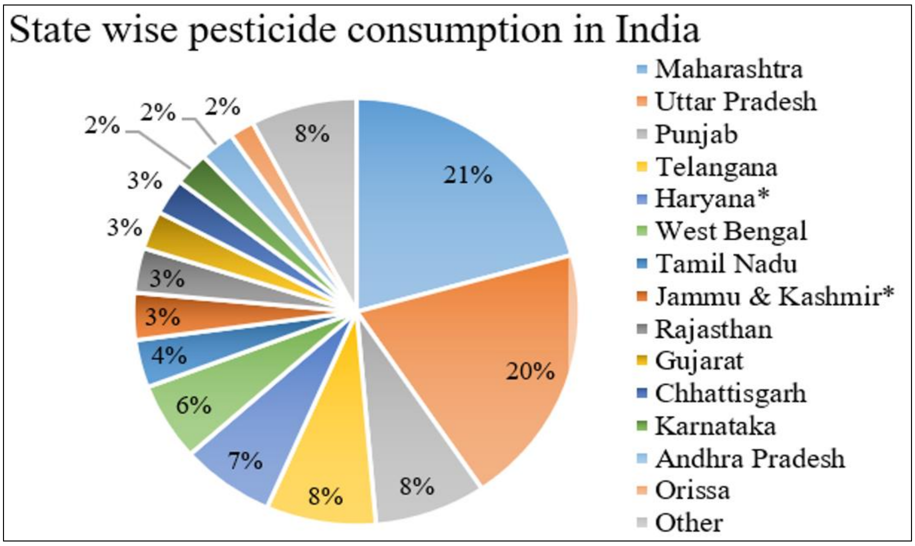
Pesticide usage in India differs from that in the rest of the world. Currently, the most common pesticides in India are insecticides, followed by fungicides and then herbicides (Nayak *et al*., 2021) [18]. On the other hand, the global pesticide pattern involves herbicides, followed by insecticides and then fungicides. At present, India ranks fourth worldwide in pesticide production. According to Research and Markets, the Indian pesticide industry was worth Rs. 214 billion in 2019. The market is estimated to touch a compound annual growth rate of 8.1 percent and reach 316 billion by 2024 (Nayak *et al*., 2021) [18]. India began to produce pesticides in 1952 when the facility for manufacturing BHC in Calcutta was created. Currently, India is the second largest producer of pesticides in Asia. In India, there are about 293 pesticides registered, and it is stated that 104 pesticides are still being produced/used in the country, though they are banned in at least two or more states across the globe (Nayak *et al*., 2021) [18].



(**Source:** http://www.fao.org/faostat/en/#data) (FAO, 2018) [8]

Fig 2: Pesticide use pattern India

Both total and per-hectare consumption of pesticides in India shows a significant increase after 2009-10. Notably, 50% of all insecticides used for pest management in India are directed towards cotton pest control. The major pesticide-consuming crops are cotton (40–50%), followed by rice (20%), vegetables and fruits (13–24%), coarse grains and oilseeds (6–7%) and sugarcane (2–3%) (Subash *et al.*, 2017) [26]. In 2017, the per-hectare pesticide usage in India was relatively low, about 0.31 kg, whereas 19.6 kg per hectare in Saint Lucia and 16.59 kg per hectare in Hong Kong (Roser *et al.*, 2019) [23]. In 2016-17, Maharashtra had the highest total pesticide consumption, followed by Uttarakhand, Punjab, and Haryana. The highest acre per pesticide use was in Punjab (0.74 kg), followed by Haryana (0.62 kg), and then Maharashtra (0.57 kg). According to the data, Maharashtra and Uttar Pradesh contribute to 41% of India's pesticide consumption (Nayak *et al.*, 2021) [18]. The northeastern states like Meghalaya, Sikkim, Nagaland, Manipur, Mizoram, and Arunachal Pradesh consume minimal pesticides (less than 100 tons each). The remaining states (Assam, Jharkhand, Chhattisgarh, Bihar, Odisha, Madhya Pradesh, Uttarakhand, Himachal Pradesh, and Kerala) exhibited pesticide consumption between 100 and 1000 tons (Kumar, 2022) [16].



(**Source:** (GOI, 2020)

Fig 3: State wise pesticide consumption in India (2019-2020)

As mentioned above pesticide consumption is the highest in Maharashtra but per hectare consumption of pesticides was the highest in Punjab (0.74 kg), followed by Haryana (0.62 kg) and Maharashtra (0.57 kg) during the year 2016-17, while the consumption levels were lower in Bihar, Rajasthan, Karnataka and Madhya Pradesh (Subash *et al.*, 2017) [26].

Table 1: Pesticide consumption per hectare

Punjab	0.74 Kg
Haryana	0.62 Kg
Maharashtra	0.57 Kg
Uttar Pradesh	0.39 Kg
Tamil Nadu	0.33 Kg
Odisha	0.15Kg
Bihar	0.11 Kg
Gujarat	0.13 Kg
Rajasthan	0.05 Kg
Karnataka	0.10 Kg
Madhya Pradesh	0.03 Kg
All India	0.29 Kg

(**Source:** Pesticide Use in Indian Agriculture: Trends, Market Structure and Policy Issues)

Pesticides and Soil health

Soil acts as the major descendant of applied pesticides. Nearly 10% of applied pesticides reach their targets after application (Gill *et al.*, 2014) [9]. Further, pesticides like fumigants, nematicides, herbicides, etc. applied to the soil directly contribute to the pesticide sink of the soil. The major processes involved after pesticide application are adsorption, desorption, leaching, volatilization, and degradation (Pathak *et al.*, 2022) [20]. Directly or indirectly pesticides come to soil and get adsorbed onto the soil. Soil textural class plays a significant role in determining pesticide's adsorption. Adsorption of a pesticide molecule is directly related to the clay and oxide/hydroxide contents of the soil. These get adsorbed better in clay soil (Rasool *et al.*, 2022) [22]. Higher SOM results in higher adsorption of pesticides as SOM acts as a potent adsorbing site for pesticides. Soil pH influences the ionization of clays/SOM surfaces and the pesticide molecules (Locke *et al.*, 2004) [17]. Further, soil properties like water content, temperature, etc. significantly influence pesticide adsorption onto the soil (Pathak *et al.*, 2022) [20]. The basic properties of pesticide molecules like water solubility, vapour pressure, and pKa or pKb value also influence the adsorption behaviour onto soil. The highly adsorbed pesticides are less available for leaching/degradation. Higher precipitation results in more dissolution of highly soluble pesticides and resulting in lower adsorption and high pesticide leaching. Similarly, in dry seasons, pesticides with high vapour pressure show evaporation losses from the soil and more concentration in soil water. Therefore, a pesticide residue gets stored in soil and moves from soil to water/air and continues its pollution cycle. Pesticides can be effective in protecting crops from pests; they can also have both short-term and long-term impacts on soil health.

Due to all these processes soil health is severely affected and soil becomes unfit for cultivation as growing crops in pesticide-contaminated soil poses a serious challenge of bioaccumulation and bio magnifications of pesticide residues in higher organisms. The soil's normal physical, and biological properties and its micro life get damaged causing huge losses to its soil fertility and productivity. These show negative effects on non-target organisms and other beneficial species. Further movement of these pesticides to groundwater due to leaching and runoff causes contamination of the water table.

Effects of pesticides on soil health

Soil Microorganisms: Pesticides, especially broad-spectrum ones, can harm beneficial soil microorganisms. These microbes are essential for the breakdown of organic matter, cycling of nutrients, and enhancement of soil structure. When pesticides reduce their populations, they can disrupt these essential processes, affecting overall soil health.

Residue Accumulation: Pesticide residues can accumulate in the soil over time, particularly if they are used frequently. These residues have a longer half-life in the soil, which could alter its properties, contaminate groundwater, and have long-term effects on the soil's health. Soil microorganisms and other biotas may have a limited capacity to break down these pesticide residues. Many herbicides can be detrimental to soil organisms that are not intended targets such as earthworms which are essential for soil aeration and nutrient cycling.

Pesticide Mobility: Certain pesticides can contaminate groundwater by seeping through the soil, which can cause harmful effects on the environment and human health. Pesticides can contaminate nearby water bodies off-site as a result of moving through the soil profile. Groundwater and surface water contamination can also result from runoff from pesticide-treated fields. This pollution can negatively affect aquatic ecosystems and cause a threat to drinking water supplies.

Ecosystem Disruption: Pesticides can harm beneficial soil organisms such as earthworms, microorganisms, and other beneficial insects. This can disrupt the natural balance in ecosystems and negatively impact biodiversity.

Soil Structure and Composition: Pesticides alter the physical and chemical properties of the soil. This can lead to poor soil fertility, reduced water retention capacity, and impaired nutrient cycling. They affect soil structure by reducing the activity of earthworms and other soil organisms that help maintain soil porosity and structure. Compacted soil can lead to reduced water infiltration, increased erosion, and decreased root growth. They may lead to the degradation of soil aggregates which can reduce water infiltration and aeration. This can make the soil less hospitable to plant roots and soil-dwelling organisms.

Reduced Biodiversity: Pesticides may harm non-target organisms in the soil, including earthworms, insects, and other beneficial organisms. This causes a loss of soil biodiversity, which is essential for maintaining a healthy soil ecosystem.

Soil pH: Some pesticides can alter the pH of the soil. For example, certain herbicides can make the soil more acidic. Changes in soil pH can affect nutrient availability and the overall health of soil organisms.

Nutrient Cycling: Pesticides can disrupt nutrient cycling in the soil. For example, the use of herbicides can affect the decomposition of organic matter and the release of nutrients from organic materials. This causes negative effects on soil fertility.

Runoff and Contamination: Pesticides can leach into groundwater or be carried by surface water runoff into nearby water bodies. This can lead to water contamination, affecting aquatic ecosystems and potentially human health. Contaminated water can also indirectly impact soil health when it is used for irrigation, leading to pesticide residues in the soil. Pesticides can leach into the soil and persist for extended periods, potentially contaminating groundwater and affecting the health of soil organisms. This contamination can lead to long-term ecological and environmental issues.

Resistance and Pest Outbreaks: Prolonged or extensive pesticide use can lead to the development of pesticide-resistant pests. This can result in the need for higher pesticide application rates or the use of more potent pesticides, which can exacerbate the negative effects on soil health, and can worsen pest problems in the long run.

Impacts on Beneficial Insects: Although they have nothing to do with soil health, pesticides can damage beneficial insects like pollinators and crop pests' natural predators. These insects influence pest populations, which has an indirect impact on soil health and contributes to the upkeep of ecosystem equilibrium. When it comes to these non-target creatures, such as insects, birds, and other wildlife, pesticides might have unforeseen effects. These species' collateral harm has the potential to lower biodiversity and disturb ecological dynamics.

Soil enzymatic activity: Pesticides affect soil enzymatic activities as they inactivate the enzymes by binding at active sites thus blocking the enzyme from acting on substrate. Soil enzymatic activities are a major indicator of soil health and are affected by excessive pesticidal usage.

Alternate sustainable methods of pest control

These alternative methods help in effective pest control along with sustainable management of soil health. These methods do not deteriorate the soil and the environment. These are cost-effective and do not pollute the ecosystem. These include:

Integrated Pest Management (IPM): It is the most effective method of pest control and minimizes losses. By combining biological, cultural, and chemical control techniques with the sparing application of chemicals only when required, integrated pest management (IPM) solutions seek to lessen the dependency on chemical pesticides. This strategy prioritizes ecologically sustainable pest management techniques while reducing the negative effects of chemicals on soil health.

Biological Pest Control: Utilizing natural predators and parasitoids can reduce the need for chemical pesticides. This approach encourages the preservation of natural enemies and promotes ecological balance in agroecosystems. Encouraging natural predators of pests, such as ladybugs, parasitoid wasps, and nematodes, can be an effective means of pest control while reducing the need for chemical pesticides.

- **Sustainable Pesticide:** Use of the less toxic pesticide, as well as adhering to recommended application rates and timing, can minimize the environmental impact of pesticide use.
- **Selective Pesticides:** Choose pesticides that have lower toxicity to non-target organisms and have a shorter persistence in the soil.
- **Soil Testing:** Regular soil testing can help determine the presence of pesticide residues and their potential impact on soil health. It can guide the selection of appropriate remediation measures.
- **Crop Rotation**: Crop rotation can disrupt the life cycles of specific pests, reducing the need for constant pesticide applications.
- **Organic Farming:** Organic farming practices often focus on reducing or eliminating synthetic pesticides, relying on organic alternatives, and promoting soil health through composting and other soil-building techniques.
- **Reduced-Risk Pesticides:** Reducing the environmental impact can be achieved by using pesticides that are less harmful and more selective. These insecticides are made to specifically target pests without endangering beneficial creatures.
- **Crop Diversity:** Increasing crop diversity can interfere with pests' life cycles and lessen the demand for insecticides. Ecosystems with diversity are more resistant to pest outbreaks.
- **Soil Health Management:** Crop resilience and pest pressure can both be increased and decreased by improving soil health through techniques like cover crops and reduced tillage. A robust ecology of beneficial bacteria and creatures is supported by healthy soils.
- **Monitoring and Thresholds:** Regular monitoring of pest populations allows for timely interventions when necessary. Setting action thresholds ensures that pesticides are only used when pest populations reach a level that threatens crop yield or ecosystem health.

Remediation of Pesticide-Contaminated Soils

During the last two decades, there have been many trials worldwide focusing on the cleanup of pesticides in soils. The molecules of pesticides have always been difficult to counteract and nullify since their degradation and dissipation usually end up determining the longevity of the molecules that may reside in the soil for even a year or two. Still, there are various techniques, including bioremediation, phytoremediation, chemical oxidation, surfactant extraction, electro-kinetic remediation, and thermal desorption, to clean up the soil (Pathak *et al.*, 2022) [20]. The two major methods used for remediation of pesticide-contaminated soils are:

- Bioremediation.
- Electro kinetic soil flushing.

Bioremediation: It includes the natural processes of pesticide metabolic activities of microorganisms, which is a cheap, safe environmental treatment and popular. The two types of bioremediation include phytoremediation and microbial remediation (Pathak *et al.*, 2022) [20]. The phytoremediation of pesticides from soil is due to plant uptake, vegetation degradation, volatilization, and combined degradation using root exudates and rhizosphere microorganisms.

Electrokinetics: It is the process used to remove or transfer pollutants from the soil into flushing fluid. The contaminated flushing fluid can be treated, or the contaminants can be mobilized by electro-osmosis, electro-migration, and electrophoresis.

To avert this, biopesticides that are primarily natural product-based and harmless to soil biota are used. Biopesticides are a broad group of natural substances derived from microorganisms (microbial pesticides), plant-derived with added genetic material (plant-incorporated protectants-PIPs), and other naturally occurring products. They have been the leading alternative to chemical pesticides and eco-friendly solutions for pest management in various countries, including India. Common and often used biopesticides include *Bacillus thuringiensis* (Bt), *Baculo* virus, *Trichoderma*, and *Azadirachta indica* (Pathak *et al.*, 2022) [20].

Conclusion

Pesticides have been a quick, convenient, and cheap way of controlling weeds and insect pests in the agricultural sector. They have been instrumental in improving the world's agricultural production and farmer's income. They have proven beneficial not only for farmers but also for people worldwide, contributing to increased agricultural yield and numerous societal benefits indirectly. However, the concern about the hazards pesticides pose to soil health and the environment has raised concerns over their safety. To ensure the safe application of pesticides, there is a need to regulate and promote the utilization of economically efficient and environmentally friendly pesticides. It is crucial to make sure that the prescribed dosage is followed precisely; as Paracelsus famously observed, "The right dose differentiates a poison from a remedy." Deregistration of obsolete and a potentially dangerous pesticide is another crucial factor. This strategy aims to create a more sustainable and environmentally friendly farming method in India.

The above conversation shows the worries over unbalanced pesticide use, resulting in different negative impacts on the environment and soil health. Various studies have questioned the safety of pesticides in the environment and soil health despite being designed to prevent, kill, or control pests. While complete eradication of the risks associated with pesticide use may be difficult, reducing the exposure and decreasing adverse effects is possible.

Adopting strategies such as IPM (Integrated pest management), organic farming, alternative farming methods, and the use of well-maintained spraying equipment can minimize exposure. Looking at the best chemicals and formulations for environmental and ecological pest management is vital. Using pesticides appropriately and only when necessary will reduce their risks. Applying less toxic formulations or lower doses of poisonous formulations can also limit destruction. Unwittingly, people may expose themselves to toxic pesticides that farmers lack knowledge of. This can be reduced by increasing awareness among the farmers about the types of pesticides, their hazards, and safety measures. It is anticipated that the use of IPM in the future will provide a more sustainable approach to pest and insect control. As a result, this protects the environment and serves multiple purposes, such as controlling pests and invasive species in urban areas. Moreover, to minimize the excessive dependence on pesticides, it is necessary to promote other sustainable and eco-friendly practices such as organic farming practices and the exploration of viable alternatives like bio-pesticides or biological agents for agricultural pest control. Scientists have been vigorously looking for new ways to reduce pesticide pollution. Some cost-effective and environmentally benevolent bioremediation approaches can be applied, such as phytoremediation, microalgae bioremediation, myco-remediation, and electrokinetics. These methods are very environmentally friendly but with limitations. Therefore, the approaches to these areas will only be successful if further research is conducted.

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