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Assessing the Impact of Pesticide use on India's Agriculture and Environment

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ABSTRACT

The Indian agricultural sector has become highly dependent on pesticides to protect the crops from pests and diseases. However, the extensive use of chemical pesticides poses a severe threat to the environment and its sustainability. This paper aims to review and analyze the trend across the country and explain the adverse consequences of pesticides on ecosystems. As pesticides can contaminate soil, water, and air resulting in serious environmental degradation, this research looks at how various pesticides affect these natural resources by causing long-term harm to ecosystems. Moreover, prolonged exposure to pesticides can also be harmful to human health. The paper examines the intricate relationship between exposure levels versus the inherent toxicity of such chemical compounds, also considering the possible health risks associated with their utilization in fields. Also, the chances of forming decomposition by-products that may be more harmful than the parent chemicals within the environmental matrix are highlighted. This paper also investigates alternative methods for the use of pesticides, paving the path for safe and organic agricultural practices that could be adopted. The study highlights the urgent need for a shift towards integrated pest management strategies, biopesticides, and precision agriculture technologies to mitigate the negative impacts of pesticides and ensure sustainable agricultural development in India.

Keywords: Pesticide; Environmental impact; Human health risks; Sustainable agriculture; Integrated pest management.

1. INTRODUCTION

Pesticides are widely used in the agricultural sector to protect crops from a variety of pests, diseases, and weeds to ensure food security (Singh *et al.* 2021). However, the excessive usage in the agricultural fields has destroyed the ecosystems as well as the human health (Dasgupta *et al.* 2009), particularly in an agrarian country like India this has become a serious problem, which requires immediate attention. Additionally, this is exacerbated by the fact that India is an agrarian economy where farming is its mainstay; consequently, there arises a very thin line between safeguarding the harvests and preserving the environment for forthcoming generations.

Using pesticides in India is a subject that has many angles. In this case, Maharashtra is the Indian state with the most usage of pesticides (Prasad *et al.* 2023), but then again, there are different regional views. Conversely, Kerala for example practices intensive farming systems and hosts diverse ecosystems which makes it imperative to develop distinct strategies. This paper aims to survey the current pesticide usage patterns, analyze their impact on the environment and human health, and explore potential alternatives to promote sustainable agriculture, with a specific focus on the states of India. There are various modes around here, like too much dependence on plantation crops or being more of a pesticide-dominated private sector retailing activity (Devi *et al.* 2018). There appears to be an alarming trend in Kerala even when reports indicate a possible decline in overall pesticide usage across India (Prasad *et al.* 2023). Menon and Muraleedharan (2017) show that there is increasing worry about per-hectare application rates in this region, whereas total volume might be decreasing. This situation may mean a sudden switch to more potent insecticides, thereby posing grave environmental threats and health risks. The danger to humans and the environment comes from highly toxic chemicals that may be applied at lower rates, but it does not mean that they are safer; rather, the risk of exposure to such toxicants becomes higher with toxicity per treated area or individual.

The prolonged use of pesticides has serious long-term repercussions on the whole agricultural ecosystem, besides providing immediate protection for the crop. Persistence in the soil can lead to complex microbial web disturbance, which is responsible for organic matter decomposition and soil fertility. This may give rise to deteriorating soil quality, more dependence on stronger chemicals, and therefore reduced soil productivity (Singh *et al.* 2009; Singh and Kapoor, 2014).

Water draining from pesticide-affected fields may leach into aquifers or flow into surface waters killing aquatic organisms, disrupting food chains, and possibly contaminating drinking and irrigation supplies (Dasgupta *et al.* 2009). Pesticide-containing waters also cause bioaccumulation of these toxicants as they pass through the food chain thereby posing human health risks. Table 1 provides an overview of the levels of pesticide contamination in different water bodies across the states in India. This data clearly shows that a lot of surface waters have been polluted by the excessive use of pesticides such as Chlorpyrifos, Atrazine, Malathion, and Fipronil in farming activities across the country (Kaushik *et al.* 2008; Indiresan *et al.* 2018; Kaur *et al.* 2021; Kumar *et al.* 2013; Reddy *et al.* 2019; Desai *et al.* 2017; Sajitha and Muraleedharan, 2021; Nair *et al.* 2023)

Respiratory problems might develop in farmers, agricultural workers, and those who live around due to the emission of harmful gases during the spraying of pesticides into the atmosphere. Breathing in such fumes leads to malfunctions like respiratory distress, eye diseases, or neurological impairments among others (Gupta, 2016; Gupta and Prakash, 2019). It is when this water, soil, or crops come into direct contact with human skin that there can be irritation on the skin followed by possible uptake of toxins capable of causing illnesses such as dermatitis and possible long-term effects (Kumar *et al.* 2013). The studies have reported that pesticide residues will be present on food products that may be consumed by individuals, particularly vulnerable groups including children and pregnant women (Pandey *et al.* 2020). Such exposure has been linked to various health risks including birth defects, some types of cancer, and neurodegenerative disorders (Kumar *et al.* 2013).

Table 1. Pesticide contamination levels across India

Pesticide	State	Crop Type	Water Body	Concentration Range (mg/L)	References
Atrazine	Punjab, Haryana	Corn, Sugarcane	River Yamuna, Groundwater	0.001 - 0.01	(Kaur *et al.* 2021; Kumar *et al.* 2013)
Chlorpyrifos	Haryana, Uttar Pradesh	Cotton, Groundnut	River Yamuna	0.002 - 0.02	(Indiresan *et al.* 2018; Kaushik *et al.* 2008)
Fipronil	Andhra Pradesh	Rice, Vegetables	Groundwater	0.001 - 0.01	(Reddy *et al.* 2019; Desai *et al.* 2017)
Malathion	Madhya Pradesh	Wheat, Pulses	River Narmada	0.0005 - 0.005	(CPCB, 2021)
Profenofos	Kerala	Rice	Groundwater, Rivers	0.005 - 0.02	(Sajitha and Muraleedharan, 2021)

2. ROLE OF PESTICIDES IN AGRICULTURE

Pesticides are a large group comprising different chemicals employed in farming and classified according to the pests they target like insecticides that fight insects, herbicides that control weeds, fungicides that mitigate fungal infections, or rodenticides developed to deal with rodent populations. Insecticides play an important role not only by preventing or controlling harmful insects that may destroy crops but also result in retarded growth, low harvests, or even no output at all. The most common representatives among these insects are locusts, beetles, worms, and lice (Aktar *et al.* 2009). In India, insecticides are widely used in crops such as cotton, rice, vegetables (brinjal, tomato, okra), pulses, oilseeds, sugarcane, and fruits to protect crop yields from various insect pests. Locusts, swarming in devastating numbers, can devour entire fields in a matter of hours, while beetles wreak havoc by boring various plant parts, reducing yield. Caterpillars, the ravenous larvae of butterflies and moths, consume vast quantities of leaves, hindering plant growth, and tiny aphids weaken plants by sucking sap and can even spread diseases between them.

Herbicides target unwanted weeds that compete with crops for vital resources like water, nutrients, and sunlight. Uncontrolled weeds can significantly impede crop growth and development, leading to reduced yields and economic losses for farmers (Carvalho, 2016). Herbicides are employed across various crops in India, including rice, wheat, maize, sugarcane, groundnut, cotton, chilies, and tomatoes. The choice of herbicide depends on the specific crop, weed species, and environmental conditions. The high-productivity areas of north-western India, particularly in states like Punjab, Haryana, and Uttar Pradesh, are known for extensive herbicide use, such as fluchloralin, atrazine, and glyphosate, in crops like rice, wheat, and sugarcane. (Aktar *et al.* 2009)

Fungicides are essential for controlling fungal diseases that can damage or destroy crops, manifesting as blights, mildews, and rusts, causing significant yield losses across various crops like wheat, rice, and fruits. Fungicides are widely used in India on various crops like rice, wheat, sugarcane, cotton, pulses, fruits, and vegetables. States such as Punjab, Haryana, Andhra Pradesh, Maharashtra, and Karnataka are major users due to their intensive agricultural practices (Kumar *et al.* 2020).

Rodenticides play a crucial role in controlling rodents that can munch on stored grains and cause damage to agricultural infrastructure. This poses a significant threat to food security, especially in areas with limited storage facilities. In India, rodenticides are widely used to protect crops like cereals (rice, wheat), sugarcane, and pulses from rodent damage. States with high rodent populations, like Punjab and Rajasthan, tend to use more rodenticides (FAO, 2022). Figure 1 shows the percentage usage of pesticides in India.

Pesticides offer multiple advantages to agriculture beyond just pest control. By safeguarding crops from pests and diseases, pesticides contribute to producing higher-quality produce, enabling farmers to fetch better prices in the market (Popp *et al.* 2013). This improved crop quality translates to increased income for farmers. Additionally, effective pest control facilitated by pesticides leads to higher crop yields, which is crucial for feeding our ever-growing global population (Aktar *et al.* 2009). Moreover, these substances also help minimize post-harvest losses, aid in transportation, and ensure food security (Oerke, 2006).

Indiscriminate use can lead to environmental pollution, where pesticide residues remain in the soil and water. This affects beneficial organisms such as insects or pollinators, disrupting the ecological balance (Aktar *et al.* 2009; Sanchez-Bayo and Wyckhuys, 2019). People's health is also at risk, as farmers, farm workers, and consumers can be exposed to pesticides through inhalation, ingestion, or skin contact, which can cause health issues (Mostafalou and Abdollahi, 2017). Relying too much on a single pesticide may backfire, as pests can develop resistance, rendering the chemical ineffective. This often necessitates the use of stronger pesticides or alternative control measures (Gould *et al.* 2018).

Pesticides have other positive effects apart from their role in pest control. For example, desiccants quicken the drying pace of crops before harvesting to achieve proper moisture content for storage thereby avoiding spoilage and improving the general standard (Gayathri *et al.* 2011). On the flip side, defoliants precipitate leaves to fall off earlier by employing chemicals that can help make the harvesting process easier and enhance air movement in dense crops thus preventing moisture-related diseases (Mithila and Kharbanda, 2016). However, pesticides used in crop protection come with certain drawbacks. The broad-spectrum application of pesticides leads to the pollution of the environment through toxic residues that kill soil and water-beneficial organisms (Aktar *et al.* 2009; Sanchez-Bayo and Wyckhuys, 2019). Equally important is human health as they can be exposed through breathing, swallowing, or touching by farmers including both agricultural workers and even consumers who are subjected to risks associated with pesticides leading to different disorders (Mostafalou and Abdollahi, 2017). Punjab and Rajasthan are two such states where high rat populations have been noted (FAO, 2022).

Another advantage of pesticide use is that it allows farmers to produce higher quality products hence fetching a premium price for them thereby raising their incomes (Popp *et al.* 2013). For example, effective pest management increases crop productivity which is crucial in feeding the world's growing population (Aktar *et al.* 2009). The overreliance on specific pesticides can lead to pests developing resistance, making these chemicals less effective over time. This necessitates the use of stronger pesticides or alternative pest management methods, as discussed by Gould *et al.* in their 2018 study on pest resistance management.

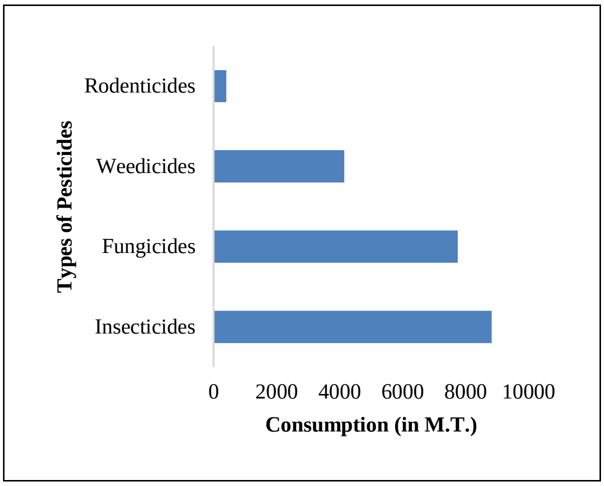

Fig. 1: Various Pesticides usage in India (Source: Directorate of Plant Protection, Quarantine & Storage, Ministry of Agriculture and Farmer Welfare)

3. PESTICIDE USAGE PATTERNS ACROSS INDIA

Pesticides come in various forms tailored to target different agricultural pests – insecticides tackle insects, herbicides combat weeds, fungicides fight fungal diseases, and rodenticides control rodents. Figure 1 illustrates how these different pesticide categories were consumed across India during 2022-23.

Insecticides play a crucial role by eliminating insects that can wreak havoc on crops, devouring leaves and stems, stunting growth, and even causing complete crop failure. Common culprits include ravenous locusts that swarm in biblical proportions, crop-boring beetles, leaf-munching caterpillars, and sap-sucking aphids that can also spread plant diseases (Aktar *et al.* 2009). Across India, insecticides safeguard vital crops like cotton, rice, vegetables, pulses, oilseeds, sugarcane, and fruits from these pests.

Herbicides, on the other hand, target the weeds that compete with crops for precious water, nutrients, and sunlight. Unchecked weed growth can severely impede crop development and yields, dealing a major economic blow to farmers (Carvalho, 2016). Indian farmers rely on herbicides for crops like rice, wheat, maize, sugarcane, groundnut, cotton, chilies, and tomatoes. The herbicide chosen depends on the specific crop, weed type, and environmental conditions. The high-productivity belt of northwest India, especially Punjab, Haryana, and Uttar Pradesh, is a hotspot for herbicide use on staples like rice, wheat, and sugarcane, with products like fluchloralin, atrazine and glyphosate (Aktar *et al.* 2009).

Fungicides are essential for controlling the fungal blights, mildews, and rusts that can devastate crop yields across wheat, rice, fruits, and more. These fungicides see widespread use in Indian agriculture on crops like rice, wheat, sugarcane, cotton, pulses, fruits and vegetables. Major users include states practicing intensive cultivation like Punjab, Haryana, Andhra Pradesh, Maharashtra, and Karnataka (Kumar *et al.* 2013).

Rodenticides serve to protect stored grains from rodents that can inflict huge losses and jeopardize food security, especially where storage facilities are limited. Across India, rodenticides safeguard cereal crops like rice and wheat, as well as sugarcane and pulses from rodent infestations. Punjab and Rajasthan are two such states where high rat populations have been noted (FAO, 2022).

Another benefit of pesticide use is that it allows farmers to produce high-quality crops thus enabling them to earn premium prices for their products and therefore increase their incomes.'' (Popp *et al.* 2013). For example, effective pest management increases crop productivity which is crucial in feeding the world's growing population (Aktar *et al.* 2009). Besides reducing post-harvest losses, pesticides also ease the transportation and storage of harvested grain thus ensuring food security Oerke, 2006 has reported that usage of these chemicals led to less damage caused on stored foods. Farming areas like Punjab and Rajasthan with a large number of rats have the highest rates of consumption (FAO, 2022).

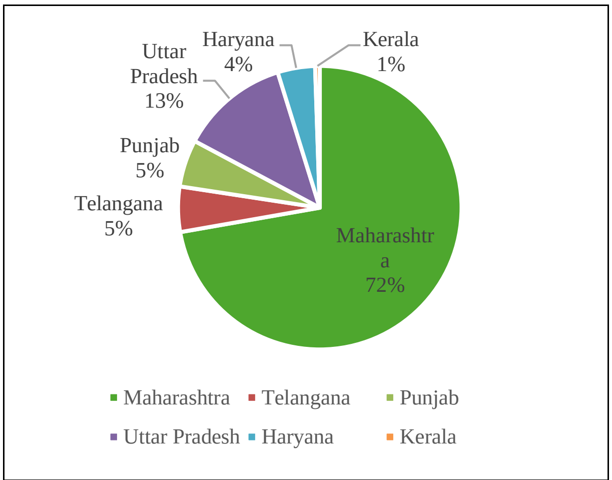

Fig. 2: Pesticide usage in various Indian states (Source: Ministry of Agriculture and Farmer Welfare)

On the other hand, there are trade-offs associated with these benefits. Indiscriminate spraying of pesticides can cause environmental pollution as residues remain in soil and water, thereby harming beneficial insects, pollinators and disrupting ecosystems (Aktar *et al.* 2009; Sanchez-Bayo and Wyckhuys, 2019). Furthermore, inhalation, ingestion, or skin contact with pesticides may result in certain diseases that can be worrisome considering that they reach farmers and agricultural workers as well as final consumers (Mostafalou and Abdollahi, 2017) Finally, overreliance on a particular pesticide can also develop pest resistance prompting the use of stronger formulations or alternative methods for controlling them (Gould *et al.* 2018).

Pesticides are useful for other purposes other than controlling pests. For example, moisture in crops is reduced faster by desiccants to optimize storage conditions and reduce spoilage to enhance quality (Gayathri *et al.* 2024). However, notwithstanding their importance as crop protection agents, pesticides must be used carefully and sparingly. Spraying too much can cause pollution of surroundings that will destroy life including humans (Aktar *et al.* 2009; Sanchez-Bayo and Wyckhuys, 2019; Mostafalou and Abdollahi, 2017). In addition, pest tolerance may diminish their efficacy necessitating other strategies (Gould *et al.* 2018).

The pie chart in Fig 2, gives an insight into what percentage of pesticide is used in different major states in India according to 2022-23 data from the Indian Government's Statistical Database. Maharashtra is a leading consumer and accounts for an astonishing figure of about 72% of national pesticide consumption (Dhole *et al.* 2017). This is because it has large farms that produce cotton, fruits, vegetables, and others that are heavily reliant on pesticides to guard against damage to their crops. Nevertheless, monoculture cultivation whereby a vast expanse of land is dedicated to growing one crop alone can generate conditions conducive to doubling the number of pests (Shree and Desai, 2014).

Other states such as Punjab, Haryana, Uttar Pradesh, and Telangana also have alarming levels varying from 5-13%. Like Maharashtra though they have wide agricultural areas where crops are grown intensively resulting in increased reliance on chemical pesticides due to factors such as monoculture and pressure for high yields.

In contrast, Kerala has shown that it is a state where over the years pesticide use is relatively lower. The difference is underpinned by several factors. Kerala's agricultural landscape however varies greatly, with smaller landholdings and more diversified crop patterns. It also has a historical tradition of emphasizing natural pest management instead of chemical control in organic eco-friendly farming. Yet, some areas within Kerala have rather high pesticide intensity due to factors such as monoculture systems, pest outbreaks, crop types, agro-climatic conditions, and market demands (Devi, 2010).

Findings show that while Kerala generally uses less pesticides than other states among vegetable farmers there are various levels of reliance on pesticides. Some farmers prefer Integrated Pest Management (IPM) and organic practices to reduce chemical inputs and promote sustainable agriculture (Sachin *et al.* 2013). However, others depend fully on conventional pesticide applications due to the limited availability of alternatives; market pressures for attractive-looking produce, and belief systems about efficacy (Gopakumar *et al.* 2017). Fig 3 indicates that there was a small decrease in India's use of chemical pesticides from 2018-19 to 2022-23. According to the Ministry of Agriculture and Farmers Welfare, total consumption decreased from 59,670 metric tonnes in 2018-19 to 53,000 metric tons in 2022-23. This decline may be due to increased knowledge about environmental and health risks associated with pesticides, farmer uptake of IPM, policy initiatives for sustainable agriculture, and other studies presenting biopesticide options as well as organic farming. Nevertheless, such developments must overcome growing challenges including pest resistance and changing agricultural landscapes through continued vigilance and prudent use of pesticides that promote sustainability while protecting human health and the environment.

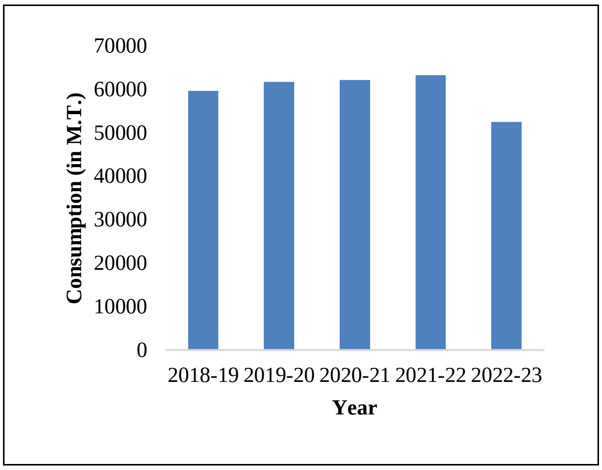

Fig. 3: Pesticide usage from 2018-2023 (Directorate of Plant Protection, Quarantine & Storage, Ministry of Agriculture and Farmer Welfare)

4. PESTICIDE USE IN KERALA

The complicated situation of Kerala's diverse agricultural landscape regarding the use of insecticides and pesticides is evident. This reliance is largely seen on the fertile plains that spread across the entire state, mainly used for rice farming. The control of weeds and insects that are a threat to rice harvest is usually done using herbicides and insecticides (Menon and Muraleedharan, 2017). Further moving towards the midland regions, attention shifts to cash crops such as tea, coffee, cardamom, and rubber plantations. At this point there are fungal diseases which are a serious problem hence it requires those diseases to be exterminated through fungicidal application. Fungicides constitute some measures taken against such pests besides insecticides like tea mosquito bugs and mealybugs (Kumar *et al.* 2013; Ajithkumar *et al.* 2010). On the other hand, in fruit and vegetable production in the highlands, many types of insecticide arrays and fungicides are used for different pest occurrences (Jayakumar *et al.* 2001).

Despite Kerala's consumption of these chemicals being among the lowest in India when compared with other states, there has been an alarming trend observed by researchers: a shift from older less potent pesticides to more potent ones. This transition exposes great risks to public health and the environment within the state limits. When certain pesticides tend to get overused by farmers because they have become resistant as well as their ineffectiveness due to the development of stronger formulations the process can go viral putting humans' lives in danger (Kumar *et al.* 2013).

This could be since pests have become resistant to certain pesticides through their overuse, coupled with the priority on high-value crops such as cardamom and vegetables where farmers are likely to seek stronger and more effective chemicals to minimize yield losses leading them to dependency on stronger chemicals.

In rice cultivation, herbicides are used to fight against weeds that compete with rice plants like butachlor and atrazine, while insecticides kill pests such as brown planthopper or leaf rollers (Menon and Muraleedharan, 2017). For plantations, copper oxychloride and Bordeaux mixture are fungicides used against tea, coffee, and cardamom fungal diseases (Kumar *et al.* 2013). Endosulfan was an active ingredient in plantations for many years; however, it is now prohibited because of environmental concerns (Ajithkumar *et al.* 2010). Vegetable farming and fruit growing require different pesticides depending on what is being cultivated. Fruit farmers use different types of pesticides depending on the crop type in question while others target caterpillars or even other insects causing diseases like powdery mildew or blight (Jayakumar *et al.* 2011).

The possible progression towards stronger chemicals should create fear among people based on its serious implications. These can harm the useful pollinators that assist in fertilizing crops thus affecting their reproduction systems making them unable to increase in numbers since they will not bear fruits anymore thereby reducing their population sizes on earth. (Jeswani *et al.* 2017). Humans' health is also at stake since farmworkers and consumers can be exposed to such chemicals which may lead to various health problems (Jayaraj *et al.* 2016; Kuehn, 2017). The need for sustainable pest management in Kerala to protect public health and the environment cannot be overemphasized.

IPM appears as a promising solution that calls for using cultural practices, biological controls, and simpler pesticides only when necessary (Carvalho, 2016). This will provide safer alternatives by studying biopesticides derived from natural sources (Aadil *et al.* 2022). However, success lies in teaching farmers about safe handling, alternative methods as well as responsible use of these chemicals (Jayaraj *et al.* 2016). By identifying current patterns, and probable dangers and promoting long-term solutions where Kerala could meet these challenges head-on creating a way that ensures agricultural productivity coexists with environmental protection and public health.

5. PESTICIDE IMPACTS ON THE ECOSYSTEM

Using pesticides without discretion can lead to serious consequences, interfering with the fine-tuned balance within nature and affecting soil, water, and air quality adversely. Soil vitality is at high risk due to the use of pesticides. Earthworms, nematode worms as well as fungi which aid in nutrient cycling, decomposition, and general fertility of the soil are some of the important organisms in soil that can be harmed or killed by these chemicals (Hussain *et al.* 2009). These organisms' decrease disrupts crucial processes causing less productive soils (Jisha *et al.* 2016). Some pesticides are also persistent organic pollutants (POPs) that degrade slowly and accumulate over time to reach toxic levels (Wang *et al.* 2020). Such pollution may impair future plant growth and food chains. Pesticides may also interfere with soil's physical structure hence its ability to hold water and nutrients leading to increased erosion and reduced fertility (Edwards, 1990). It is critical to evaluate contamination levels through methods such as high-performance liquid chromatography-mass spectrometry (HPLC-MS), gas chromatography-mass spectrometry (GC-MS), enzyme-linked immunosorbent assays (ELISA) which provide sensitive and specific analyses for detecting pesticides in soil samples ((Sreedhar and Prasad, 2023).

Water resources are also exposed to the danger of pesticide pollution. Contaminated surface waters including rivers, streams, and lakes caused by pesticides during rainfall can therefore compromise aquatic life and ecosystems. There is still a risk of them being hazardous especially when they are used for human drinking or irrigation (Singh *et al.* 2002). Moreover, in regions that use groundwater for drinking water the availability of water is affected as certain pesticides leach into it via soil (Battaglin *et al.* 2019). In addition to suggestions like biosensors, various analysis methods such as HPLC-MS, GC-MS, and immunoassay have been applied so far (Li *et al.* 2020; Rodriguez-Mozaz *et al.* 2007).

Ignoring air quality is not possible. The use of specific pesticides results in the formation of pollutants like ground-level ozone through evaporation of volatile organic chemicals (VOCs) mixed with other atmospheric substances present within the environment which affects respiratory health (Cleveland *et al.* 2009). Moreover, increased inhalation risks among farm workers can lead to respiratory hazards and also increase their exposure to other health effects such as respiratory issues (Jayaraj *et al.* 2016).

It is possible to counter such negative effects by developing a multi-pronged strategy. IPM which is of the preventative kind, close monitoring, and limited use of chemicals with habitat modification or natural predators as its mainstay will be helpful in this regard (Carvalho, 2016). Applied in precision agriculture, drones and sensors allow for targeted application thus reducing pesticide wastage and environmental pollution. The use of biopesticides derived from naturally occurring sources shows the potential to substitute conventional chemical pesticides in a bid to control pests effectively yet in an environmentally friendly manner (Aadil *et al.* 2022). By taking these approaches on board, it will be possible for agriculture to flourish in tandem with public health and the environment.

6. HEALTH IMPACTS OF PESTICIDE USE

Despite the disadvantages that keep them away from human health by many ways of their entry into the body system, pesticides are indispensable for enhancing agricultural output. Exposure at workplaces is the most vulnerable area for farmers themselves. For instance, farm laborers, farmworkers, and pesticide applicators have a high risk since they get into direct contact with these substances through various processes of crop production like mixing, spraying, and harvesting (Jayaraj *et al.* 2016).

However, the main challenge regarding pesticides in agriculture is that they boost agricultural productivity but are toxic to humans. For instance, there is a serious concern about occupational exposure among farm practitioners. Among other factors, high risk occurs when farm workers and other labourers who perform pesticide application come into contact with them directly on several occasions as they engage in various crop production activities such as mixing, spraying or harvesting (Jayaraj *et al.* 2016). There are some activities like inhalation by mouth or getting it through the skin of solvents that may lead to poisoning acutely or cause chronic health effects. The food can get persistently contaminated with these chemicals, therefore dietary exposure from residues found on crops post-harvesting can be another way. People in general can be exposed for a long time leading to chronic health effects if they eat crops that have been contaminated in this manner. Moreover, indiscriminate use of pesticides can pollute air, water, and soil hence those living nearby will be environmentally exposed (Fenske *et al.* 2013). People who rely on polluted water sources or live within areas where pesticides are heavily used may inhale them, ingest them, or even absorb them through their skin.

The severity of the health impacts depends on such factors as the particular pesticide, level, and duration of exposure, as well as individual differences in age and state of health (Wang *et al.* 2017). Acute poisoning may develop following high-level single exposures, thereby producing immediate symptoms like nausea, vomiting, dizziness, and headaches followed by respiratory failure, or even death. Long-term, repeated exposure to even low levels can lead to chronic health problems affecting different bodily systems. Pesticides can disrupt the nervous system, potentially causing memory loss, tremors, and Parkinson's disease, with organophosphate pesticides particularly affecting brain development and function. Some pesticides have been linked to an increased risk of certain cancers, including leukemia, lymphoma, and prostate cancer (Alavanja *et al.* 2009), thought to be associated with DNA damage. Interference with the hormonal system of Pesticides can cause endocrine disruption, reproductive problems, developmental problems in children, and metabolic disorders (Hayes *et al.* 2006). It could even lead to sterility or birth defects due to changing the synthesis of sex steroids. Moreover, it can irritate the lungs and exacerbate preexisting respiratory conditions such as asthma (Fenske *et al.* 2013); this poses more danger, especially to people who reside around water bodies that are highly contaminated with pesticides fallouts or those who work in a highly concentrated environment. The human health implications of pesticide contact cut across both short-term and long-term effects (Kumar, 2013). Furthermore, continuous exposure over long periods at low levels has also been linked to many serious illnesses. On another note, chronicity (Persistent) may bring about complications like miscarriages, birth defects, or even some cancers (Kumar, 2013). Even neurological symptoms like Parkinson's disease, memory loss, and attention deficit hyperactivity disorder (ADHD) are among them when people are continually exposed to these chemicals (Kumar, 2013). This is in addition to the fact that the effects can be severe or lead to loss of lives. Common signs of acute pesticide poisoning may include headaches, vomiting, diarrhea, and seizures (Du Toit, 2000). In contrast, a single high-level exposure might lead to acute health effects (Kumar, 2013). Likewise, reproductive problems like birth defects and miscarriages have also been reported among individuals who had long-term exposures (Kumar, 2013). Such symptoms can be easily mistaken for other illnesses making diagnosis of acute pesticide poisoning difficult. Hence children are at a greater risk from pesticide toxicity than adults because they are still developing bodies (Kumar, 2013). The fact remains that their tiny body size implies a higher relative dose in comparison with adults while their organs-in-waiting are more fragile. Although everyone is at risk from using pesticides in terms of health children are probably the most vulnerable group. Owing to their growing bodies and higher food consumption per body weight that may result in neurodevelopmental disorders or childhood cancers (Whyatt *et al.* 2002). Another group that is easily affected by exposure to pesticides includes pregnant women and their unborn babies. This can cause birth defects, low weight in child at birth or neurodevelopmental problems (Ruz-Jarabo *et al.* 2017). To protect vulnerable groups therefore, it is important to have more stringent regulations on pesticide use and greater awareness among those who handle them and live close to where they are used.

7. PESTICIDE BY-PRODUCT FORMATION AND IMPACT

The presence of pesticides in the environment does not end after application; they undergo transformations leading to side effects that can be unwanted or even dangerous. It is a complicated challenge, therefore, to understand this transformation process.

Different environmental processes bring about a transformation of chemicals in pesticides into new forms. In general, microbe degradation, chemical degradation, and finally physical processes are responsible. Pesticides decompose in soil and water due to bacteria, fungi, and other microorganisms (Microbial degradation). It might be expected that biodegradation would help remove the original pesticide; however, it can result in by-products with different properties that may be less desirable (Singh *et al.* 2009; Pillai *et al.* 2023). Chemical pesticide degradation happens when the pesticide molecules react with other chemicals such as water or sunlight leading to chemical hydrolysis or photolysis, which degrades the parent compound as well as generates by-products (Hurtado-Sanchez *et al.* 2017). The original lifespan of a pesticide can be influenced through physical processes like volatilization (evaporation) and adsorption (sticking to soil particles); as determining where byproducts may occur at later times (Huang *et al.* 2003).

Properties of such pesticide by-products may differ significantly depending on what the parent pesticide was and which pathway it went through. However, persistence, toxicity, and unintended effects are some issues associated with these products. Moreover, certain by-products may be more persistent than the main parent compound since they break down slowly and accumulate in the environment leading to long-term contamination threats (Xu *et al.* 2020). Some may be more toxic than their primary source which poses a menace to beneficial soil and aquatic organisms (Brain *et al.* 2004). Also, another major ecological and health impact might be due to some of them acting as endocrine disruptors that interfere with hormonal function in humans and wildlife (Wang *et al.* 2013). Many pesticide derivatives go unaccounted for where the registration process concentrates on the parent compound and pays little attention to any possible by-products. This makes it difficult to fully appraise the environmental and health hazards of pesticides, which is a major problem.

Dealing with this byproduct issue requires several steps. Even though IPM is vital for this purpose, a reduction in pesticide usage also leads to a decrease in the formation of by-products (Carvalho, 2016). However, these aspects are often ignored within the existing regulatory frameworks necessitating improvement of environmental risk assessments during the registration stage of a pesticide that considers by-products' formation and risks. Investment in research becomes necessary since informed choices demand knowledge of the formation, properties, and environmental fate of such by-products. By recognizing the complicatedness arising from the transformational processes of pesticides and the probable threats they may cause through the production of other compounds we can seek a sustainable path towards pest control techniques that minimize unforeseen negative impacts on both our environment as well as personal well-being.

8. ALTERNATIVES TO PESTICIDES AND THEIR ADVANTAGES

Too much use of chemical pest controls poses a great risk to our environment and health. However, there are several other ways we can do it without harming the ecosystems or undermining sustainable agriculture.

8.1 Integrated Pest Management

A successful pest control strategy is based on IPM which involves preventative measures and a variety of approaches. In IPM, species population monitoring discussions will ensure that the focus remains on whether action is required or not. This way, misuse of pesticides that may disrupt ecological systems can be avoided.

IPM also encourages alternative cultural practices that change the environment in which plants grow to deter pests from infesting them. Cultivation of diverse crops, different tillage methods, and sometimes adding more plants are some examples of cultural techniques that reduce pest numbers drastically. IPM besides watching out for insects and diseases has other biological options. This is through making use of "biological control" where the natural ability of nature to fight pests is exploited by introducing artificial enemies such as parasites, predators or diseases targeting particular pests. For instance, modifying habitat could attract beneficial insects or direct release of biocontrol organisms thereby making it more sustainable. Dealing with the impacts of pesticides needs a comprehensive approach. IPM supports preventive measures and continual monitoring to focus on non-chemical alternatives like releasing natural enemies and manipulating environmental conditions to discourage pest incursion. Additionally, technological advancement in precision farming tools reduces wastage and impact on the ecosystem during targeted pesticide application processes. In addition, using biopesticides sourced from natural materials.

There is a need for an all-inclusive approach to minimizing people-authority contact and at the same time safeguarding public health against pesticides. Strict rules on pesticide application and maximum residue levels must be developed to encourage safe practices in terms of safeguarding consumer welfare. Education disseminates information about challenges posed by pesticides to farmers and other members of the public as well as how they can be safely handled. This way, saving thousands of lives and conserving our planet will be possible through supporting organic agriculture that does not involve any pesticides whatsoever. There is a problem with pesticide by-products Thus, while it reduces both input costs and pest populations, IPM lowers its chemical applications so that fewer byproducts are produced from reducing pest populations; nevertheless, this perspective has not been added to current laws. This calls for improved environmental risk assessment in pesticide registration as well as increased investment in byproduct research. To prevent unintended consequences, it is necessary to understand how dangerous By-products are formed from pesticide breakdown. There must be more than a single approach if human exposure can be minimized and public health safeguarded. It has been seen that IPM provides an important way forward by giving priority to non-chemical methods and limiting the use of pesticides that are less toxic where appropriate. Therefore, it is important to enhance controls for application, registration, and maximum residue levels in order to encourage improved practices that would ensure consumer protection. Through education, farmers and workers should receive information on pesticide hazards; thus, they will gain skills in the proper usage of these chemicals. Lastly, supporting organic agriculture which does not use any form of chemicals at all presents a good opportunity for protecting consumers as well as farmers from exposure (Buckingham *et al.* 2012). These strategies combined ensure prudent pesticide use towards a future where food security meets with human health and ecological well-being. Excessive use of chemical pesticides in Indian agriculture resulted in issues like environmental pollution, ecological imbalance, and food residues. The Indian Government to deal with these issues, espoused the IPM as a major policy in 1985. Methods, which are used under IPM, include pest monitoring, utilization of natural enemies, and employment of biopesticides.

A 36 Central IPM Centers' network operates across India by monitoring pests and diseases; promoting the conservation of natural enemies; producing and releasing biocontrol agents; and training extension officers and farmers on IPM techniques such as the use of neem pesticides or biopesticides. This resulted in a growth rate ranging from 6.72% - 40.14% in rice fields up to 22.7%-26.63% for cotton fields following the implementation of IPM than non-IPM areas due to less damage made by pests and healthier ecosystems. As a result, the adoption of IPM in India has led to a significant decrease in chemical pesticide applications and an increase in crop yields which have been clearly shown to benefit both the environment and the agricultural industry.

8.2 Biopesticides

The pest control industry is changing significantly by coming up with biopesticides. These products are made from natural materials such as plants, animals, and even microorganisms that provide more targeted forms of synthetic chemicals. Some examples of these biopesticides include neem oil which is extracted from plant sources or Bacillus thuringiensis (Bt), a soil bacterium occurring naturally that is effective against many types of insect pests. Additionally, various microbial formulations have been developed for specific pests hence providing an exact approach for addressing different challenges facing agriculture.

In India, approximately 70% of all biopesticides are made by public organizations (Mishra *et al.* 2020). There are four hundred ten units making biopesticides spread across India with one hundred thirty units privately owned and two hundred eighty being government-owned (Mishra *et al.* 2020). Their ownership includes twenty-six central IPM center units, thirty-one ICAR/SAUs (Indian Council of Agricultural Research institutions/State Agricultural Universities), and twenty-two funded by the Department of Biotechnology (Mishra *et al.* 2020). Besides that, many public sector undertakings and biocontrol labs also contribute to the manufacturing of biopesticides (Mishra *et al.* 2020). Since 2010, the Ministry of Agriculture and Farmers Welfare has supported for establishment of biopesticide facilities at IPM centers (32) as well as commercial enterprises (35) (Chakraborty *et al.* 2023). Southern India is responsible for most of the country's production of biopesticides; however, there has been a recent inclination towards creating some facilities in northern states (Mishra *et al.* 2020). Leading government organizations involved in large-scale biopesticide production include the Central Research Institute for Dryland Agriculture, the Directorate of Oilseed Research, Kerala Agricultural University, Tamil Nadu Agricultural University, and the Central Plantation Crops Research Institute (Chakraborty *et al.* 2023). Universities like Assam Agriculture University and Central Agricultural University also manufacture biopesticides to target invasive pests (Chakraborty *et al.* 2023). In northern India, the Indian Agricultural Research Institute, Punjab Agricultural University, and G.B. Pant University produce biopesticides (Chakraborty *et al.* 2023).

Several private companies are involved too, including Biotech International Ltd., International Panacea Ltd., Ajay Biotech Ltd., Deep Farm Inputs, and Govinda Agro Tech Ltd (Chakraborty *et al.* 2023). While a small number of foreign firms are entering the Indian biopesticide market, most collaborate with domestic companies (Chakraborty *et al.* 2023).

Despite the growth, biopesticides still only make up around 9% of the total pesticide market in India (Chakraborty *et al.* 2023). However, projections indicate biopesticides could capture up to half the entire market by 2050 with an anticipated 2.5% annual growth rate (Chakraborty *et al.* 2023). The Indian government has expressed support for biopesticide use in its 2007 National Farmer Policy, recognizing its role in sustainable agriculture (Chakraborty *et al.* 2023).

Table 2 Statewise consumption of biopesticides (Source: Directorate of Plant Protection, Quarantine and Storage, Ministry of Agriculture and Farmer Welfare)

State	2018-19	2019-20	2020-21	2021-22	2022-23
Bihar	350	360	360	360	360
Chhattisgarh	505	605	605	705	740
Goa	6	6	2	5	5
Gujarat	306	307	320	392	548
Haryana	410	400	430	440	440
Himachal Pradesh	2	4	18	4	0.37
Jharkhand	41	91	91	97	93
Karnataka	544	564	561	605	454
Kerala	862	779	758	631	628
Madhya Pradesh	322	322	346	349	375
Maharashtra	1164	1082	934	934	15
Orissa	310	333	165	122	81
Punjab	246	219	210	165	172
Rajasthan	15	929	1021	1268	170
Tamil Nadu	500	820	861	891	907
Telangana	84	330	496	522	522
Uttar Pradesh	47	48	48	52	53
Uttarakhand	52	155	111	409	120
West Bengal	997	1017	1017	1017	1234

In India, the demand for biopesticides is witnessing a significant rise. There are several reasons behind this growing popularity. One is concern over the harmful effects of chemical pesticides, which can leave residues on crops that harm consumers and damage the environment by killing beneficial insects (Isman, 1997; Brahmachari, 2004). Biopesticides, made from natural ingredients like plants, bacteria, and fungi (Subramaniam, 1952), are considered safer for people and the environment, leaving minimal crop residues (Smith and van den Bosch, 1967), making them well-suited for organic farming (Peshin *et al.* 2009). Another driver is that some pests have developed resistance to chemical pesticides (Kranthi *et al.* 2002), while biopesticides work through different modes of action, maintaining effectiveness (Wahab, 2004).

The Indian government has also encouraged biopesticide use by setting up institutions for new product research and development (Manjunath, 1992); policies that promote the reduction of chemical pesticide consumption in favor of their biological counterparts by farmers (Singh *et al*. 2002). Fig.4 illustrates how pesticide usage trends in India over the years have not always followed a one-way pattern with periods of decline interspersed with instances of increase. This initial fall may be due to several reasons. One possibility might be that farmers adopted IPM Practices. Biological control, cultural practices, and judicious use of chemical pesticides are some of the methods that IPM combines to offer a comprehensive approach. Therefore, this holistic plan may have reduced the overall dependence on chemicals (Singh *et al.* 2002). Additionally, an explanation for this trend could be the arrival of new highly toxic pesticides that require less amount to be applied per use thus reducing their total consumption (Singh *et al.* 2002).

However, when specific years are considered in terms of data from the Directorate of Plant Protection, Quarantine and Storage (DPPQS), there was an increase in consumption from 59,670 metric tons (MT) in 2018-19 to 63,284 MT in 2021-22 over four years or about 6% rise. A few factors may explain this surge. For instance, ICAR has recorded enhanced agricultural output which at times results in increased input requirements such as pesticides (ICAR, 2024). In addition to that, there could also be issues such as pest resistance or outbreaks necessitating higher application rates (Shanmugam *et al.* 2017). Notably, data on DPPQS are for technical-grade pesticides and not the finished products used in fields. As a result, it may not be a direct reflection of what reaches crops. For instance, it would have been more meaningful to segregate the data on chemical insecticides from that on bio-pesticides as revealed by Mounika *et al.* (2020) in their paper titled Trends in Pesticide Consumption in India. Strangely, however, there are signs of reversing after 2021-22; hence the consumption figures for 2022-23 show a decline of 52,466 MT representing over a 17% decrease from the previous year's statistics. That drop needs to be looked into further in terms of its causes. The results may also be due to some other factors like IPM practices as recommended by the Ministry of Agriculture and Farmers Welfare (MoA and FW), or the use of biopesticides (MoA and FW, 2023).

Table 3. Different biopesticides and consumption from 2018– 2023 (Source: Directorate of Plant Protection, Quarantine and Storage, Ministry of Agriculture and Farmer Welfare)

Biopesticide	2018-19 (MT)	2019-20 (MT)	2020-21 (MT)	2021-22 (MT)	2022-23 (MT)
Ampelomyces Quisqualis			1.26	1.24	1.24
Azadirachin	113.5	134.5	117.1	258.3	227.0
Azadirachin Granules				0.7	
Bacillus Subtilis	21	21	22.6	3.3	
Bacillus Thuringiensis	81.3	82.9	108.5	138.3	143.8
Bacillus Thuringiensis Var. israelensis					0.9
Bacillus Thuringiensis Var. Kurstaki				1.9	18
Batrocera dorsalis				0.02	0.02
Beauveria Bassiana	407.9	180.7	174.2	480.0	284.4
Metarhizium anisopliae	305.4	36.1	23.07	279.7	30.6
Metarhizium Rileyi				1	1
Neem based insecticides	376.1	184.9	565.9	247.2	613.1
Nembicidine			57		0.02
NPV (H)	179.7	351.9	144.1	166.3	1.3
NPV (S)	298.5	0.4		0.39	162.7
Pascilomysis			0.3		
Pascilomysis Lilacinus	55	35.6	60.7	67.1	76.9
Pseudomonas fluorescens	371.9	401.2	592.7	533.5	704.2
Tricoderma Harzianum	10.7	23.8	10	27.3	28.8
Tricoderma Spp.	234.8	215.3	969	1253.2	170.1
Tricoderma Viride	449.7	582.6	660.9	470.5	694.3
Verticillium Chlamydosporium		0.07			
Verticillium lecanii	290.1	107.6	86.42	331.1	106.4
Other Bio-pesticides				1.89	5.67

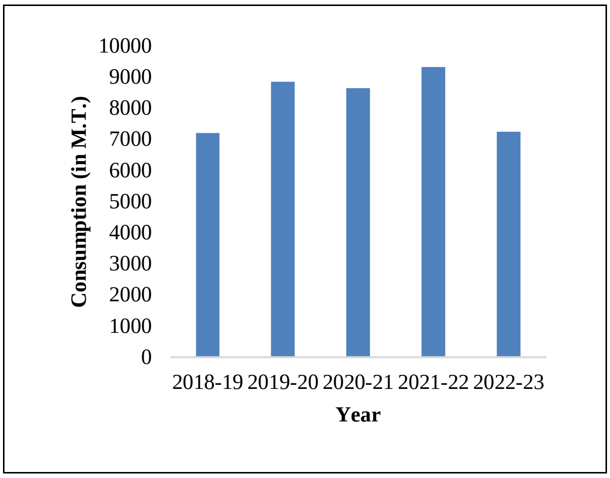

Fig. 4: Biopesticides usage (Source: Ministry of Agriculture and Farmer Welfare)

The biopesticide consumption in various states of India is presented in Table 2 and Table 3 as per the data from the Directorate of Plant Protection, Quarantine and Storage, Ministry of Agriculture and Farmer Welfare.

8.3 Physical and Mechanical Controls

These methods use physical barriers and mechanical interventions that interfere with pest activities to undertake a hands-on approach to pest management. Insect netting acts as a protective shield from unwanted flying insects, for instance. Additionally, row covers are fabric barriers placed on top of crops which may help in repelling crawling pests and affect the microclimate below them that may thus become less conducive for their survival. Traps also function well as a physical means of excluding some types of pests from the populations. Thus, physical and mechanical controls are different strategies whose aim may be eradicating or making life intolerable for pests in their localities. Moreover, these tactics can be employed in agricultural farms and homes alike. Of all the barriers used to control horticulture insect infestations, one effective one is row covers. Such covers made of plastic or polyester fibers protect plants from insects but allow penetration of light and moisture through them at the same time. It leads to dehydration by destroying the protective cuticle through which diatomaceous earth containing fossilized silica works on insects. Diatomaceous earth kills insects by causing dehydration by breaking down the protective cuticle composed of fossilized silica; however, its effectiveness reduces with moisture necessitating frequent re-application (Hossain *et al*. 2017). Traps like fly paper or sticky boards attract and capture insects, preventing crop infestation. Additionally, trap crops planted alongside main crops can trap pests away from primary plants. Fire is another farmer-employed method to eliminate pests by burning the top soil layer, although it may also harm beneficial insects and leave some larvae intact beneath the surface. Temperature manipulation serves as an effective pest control tool as well. Cold storage slows pest development and extends product shelf life, while heat treatments, like submerging mangoes in hot water, effectively kill insect larvae before export. Radiation, particularly gamma radiation, is commonly used to eradicate pests in stored products, widely utilized during grain, fruit, and vegetable exports and imports to ensure they remain pest-free. Ultrasonic vibrations, mimicking bat echolocation, can prevent pests like moths (Hossain *et al*. 2017).

Mechanical methods also play a crucial role in pest management. Handpicking, though labor-intensive, is an effective technique for the small-scale management of visible, slow-moving pests like cabbage butterfly larvae and other lepidopteran pests (Saha and Dhaliwal 2012; Arif, 2019). Bagging and screening protect crops and fruits from insect pests and prevent disease vector pests from causing damage. For instance, field bags in maize and sugarcane fields can reduce pest migration and subsequent infestation (Arif, 2019). Netting systems, particularly in apple production, have shown high efficacy against pests like the codling moth while reducing pesticide use. However, these nets can also block beneficial insects, potentially impacting natural pest control (Alaphilippe *et al.* 2016; Pajac Zivkovic *et al.* 2016). Mulching, using materials like straw, has been found to support natural pest enemies while reducing pest populations, though the cost can be prohibitive for non-organic growers (Zehnder and Hough-Goldstein, 1990).

Flooding is a traditional practice in cranberry production that helps manage pests like the cranberry fruit worm by submerging fields during critical periods. This method is effective but depends on water availability and crop tolerance (Averill *et al.* 2006). Hermetic storage technology, creating an oxygen-depleted and carbon dioxide-enriched environment, offers a significant alternative for protecting stored commodities from insects and Molds (Patrício and Rieder, 2018). Pheromone traps are widely used for monitoring and managing various insect pests through attraction and catch of the same thereby disrupting mating patterns and reducing pest populations (Arif *et al.* 2019). The benefits accruing from physical and mechanical controls cannot be ignored. These focused approaches solve directly pest issues leaving beneficial insects and pollinators that usually live in the ecosystem unharmed. There is very little harm to the environment that occurs because of them as they avoid the aftereffects usually experienced with chemical pesticides. Such a reason makes them cost-effective and sustainable long-term pest management solutions due to the ability of physical barriers such as netting to be reused.

8.4 Resistant Crop Varieties

Agricultural scientists are constantly engaged in developing crop varieties, which have built-in defense mechanisms against pests (Brookes and Barfoot, 2020). The focus of this effort is on the development of plants that naturally resist pests. Within traditional breeding approaches, it is a matter of crossing favored characters. However, modern biotechnology offers new opportunities for introducing genes with resistance to pests directly into crops (Bhatia *et al.* 2023). There are various merits associated with these pest-resistant varieties. They greatly reduce dependence on chemical pesticides by taking advantage of inherent plant resilience. This is a win-win situation that allows both the environment and food security to be improved. Resistant crops encounter fewer pest attacks thereby enhancing chances of obtaining higher yields resulting in stable food production levels. Besides, farmers would incur reduced costs due to less use of pesticides (Brookes and Barfoot, 2020).

8.5 Precision Agriculture

Precision agriculture has one great advantage, which is the power to focus on pesticide application. For instance, remote sensing and GPS-guided applicators enable farmers to locate where pests are affecting their fields. Additionally, this approach considerably reduces the number of insecticides used hence minimizing environmental pollution (Anastasiou *et al.* 2023). Besides that, precision farming is in line with IPM programs already being implemented. It keeps them informed on changes in pest population levels, weather patterns, and plant health on a real-time basis. Thus, the use of digital scouting applications or weather monitoring enables early detection of possible pest outbreaks. Therefore, before these insects reach harmful levels when they can no longer be contained biological control agents should be introduced or physical traps set by farmers (Anastasiou *et al.* 2023).

One such advantage is the reduced utilization of chemical pesticides. In general terms, it means that the interventions are aimed at reducing the total volumes sprayed thus reducing adverse effects on the environment and promoting diversity in agricultural ecosystems (Brookes and Barfoot, 2020). Precision agriculture helps to bring down pest control costs by optimizing input use. Reducing pesticide usage cuts costs and reduces the chances of pests developing resistance, a situation that means higher expenses in the future (Sreedhar and Prasad, 2023, Anastasiou *et al.* 2023). Prompt and accurate control against pest attacks helps in maintaining good crop health and avoiding yield losses due to pest damage. Crops that are healthier result in more yields and better-quality produce needed for catering to the escalating global food needs (Patrício and Rieder, 2018).

In precision farming, data analysis as well as decision support systems are important aspects. The use of artificial intelligence (AI) and machine learning (ML) methodologies has allowed for the processing of big data hence enabling predictive analytics in decision-making literacy (Patrício and Rieder, 2018). Farm management information systems (FMIS) are one such example that integrates all farm data for comprehensive farm management, operational efficiency, and resource optimization (Anastasiou *et al.* 2023). Integration of AI and machine learning techniques into precision agriculture provides farmers with valuable insights from data analysis. Such findings guide appropriate measures on pest control strategies; and farm operations such as cropping systems among others thereby leading to more sustainable and productive farming methods (Prasad *et al.* 2022). You would never believe that sensor technology is the lead in precision farming. Try to imagine a system comprising ground-based sensors mounted on satellites, drones, or tractors recording real-time information about soil moisture content, nutrient levels, and even pests and crop health status. The data collected can then be used utilizing software through advanced AI algorithms. These algorithms become a secret weapon for the farmer that predicts potential pest outbreaks (Anastasiou *et al.* 2023), recommends optimal times for pest control measures, and even generates customized treatment plans for specific zones within fields.

Precision pest management incorporates precision farming technologies to deal better with pests. This results in decreased application of pesticides, improved pest detection and management as well as an overall better crop quality (Brookes and Barfoot, 2020). Crop observation and pest detection are done using various types of sensors including cameras (RGB, multispectral, hyperspectral, and thermal) among others such as Internet of Things (IoT) based weather stations and smart traps for pest prediction and location mapping. Satellites like UAV platforms and ground robots can be used to obtain information regarding this infestation as well as introduce different ways of controlling them leading to correct management choices (Yadav and Prasad, 2023). Precision farming has many economic advantages such as reduced costs, increased profitability; environmental benefits like less chemical use and better resource management through efficient land use; and operational improvement through enhanced decision-making and targeted input application. Nevertheless, there are challenges associated with high initial expenses, complicated technology assimilation, issues of data management, and skill level requirements for operating or maintaining these systems (Prasad *et al.* 2022).

9. RESULT AND DISCUSSION

While Kerala shows lower overall pesticide consumption compared to other states, the observed trend of transitioning to more potent chemicals raises concerns. This shift is likely driven by factors like pest resistance development due to overuse of older pesticides and the need for greater efficacy in high-value crops like cardamom and vegetables. The implications of this trend are significant. Increased reliance on potent pesticides can have detrimental effects on beneficial insects like pollinators, crucial for maintaining healthy ecosystems and crop production (Jeswani *et al.* 2017). Moreover, exposure to these stronger chemicals poses higher health risks for farmers, farmworkers, and consumers (Jayaraj *et al.* 2016; Kuehn, 2017).

Promoting awareness and education among farmer groups is essential. Targeted awareness campaigns for farmers about the risks associated with potent pesticides and the benefits of sustainable alternatives are essential. Educational programs on IPM techniques can empower farmers to adopt safer practices. Also, implementing stricter regulations on the use of highly toxic pesticides and promoting the registration and use of biopesticides can help curb the trend toward stronger chemicals.

Providing subsidies and incentives for farmers to switch to biopesticides can encourage wider adoption and support the growth of the biopesticide market. Continued research to assess the effectiveness and safety of biopesticides is crucial for providing farmers with viable alternatives.

10. CONCLUSION

Pesticides have been crucial in controlling pests to enhance agricultural productivity, however their impact on environment and human health is a matter of serious concern. Indeed, there have been significant gains in crop protection and productivity due to the extensive use of chemicals in contemporary agriculture; however, it has created various environmental challenges and health risks that cannot be overlooked anymore.

It is very crucial to adopt the path of sustainability by accepting facts about dangerous byproducts and limitations inherent to traditional pest control. This review highlights the need to shift towards more sustainable pest management practices and addresses various complex issues surrounding pesticide consumption in India necessitating immediate responses towards sustainable development and responsible agricultural practices.

While overall pesticide use rests on fluctuating national figures, the alarming trend towards different potent and perhaps unsafe substances in some regions is disturbing. These chemicals build up in the soil as well as remain in the environment causing dangerous by-products that put ecosystems and human health at risk. These diverse challenges can only be addressed through a comprehensive approach with multiple strategies. This reduces the reliance on chemical pesticides by endorsing preventive approaches, biological control agents, and selective less toxic alternatives.

IPM offers a holistic approach to pest control, minimizing reliance on chemical pesticides while maximizing ecological and economic benefits. Biopesticides offer safer and environmentally friendly alternatives to conventional pesticides, reducing risks to human health and biodiversity. Precision agriculture uses only what it needs where necessary through technology thus reducing wastage and minimizing adverse effects on nature. Policymakers, researchers, agricultural communities, and society at large can tackle the complexity of pesticide use whose impacts go far to guarantee a future when we can produce food while also looking after our environment and public health. Research and development should focus on creating crops with inherent resistance to pests, reducing the need for external pesticide applications. Creating crops with resistance offers a permanent answer as it reduces external pesticide application requirements.

It is crucial to implement stricter regulations on pesticide use, support research on safer alternatives, and educate farmers and consumers about responsible pesticide management to ensure a sustainable and healthy future for Indian agriculture. Thus, responsible pest management would gain optimal results by prioritizing ecosystems' well-being, food security, and the present generation's health as well as those in future generations while reducing unforeseen outcomes. By considering these aspects, India can strive towards a future where agricultural productivity coexists harmoniously with environmental protection and human well-being.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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