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Sustainable agriculture: Exploring the potential of biopesticides

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Abstract
The review article provides an overview of the focus on sustainable agriculture and the potential of biopesticides as an alternative to chemical pesticides. It highlights the negative environmental and health impacts of synthetic pesticides and the urgent need for more environmentally friendly approaches to agricultural pest control. The aim of the development and use of biopesticides is to promote sustainable agricultural growth and protect the environment from the harmful effects of chemical pesticides. The manuscript introduces the concept of biopesticides as a sustainable solution and notes that the paper explores the development and use of biopesticides to promote sustainable agricultural growth and protect the environment.

Keywords: Agriculture, chemical pesticides, environment, bio-pesticides, pollution

Introduction

Biopesticides a useful replacement for chemical pesticides in sustainable agriculture. It discusses the harmful effects of synthetic pesticides on the environment and human health and highlights the urgent need for more environmentally friendly methods of agricultural pest control (Devi and Tarun 2011) [9]. The development and application of biopesticides as a means of promoting environmentally responsible and sustainable agricultural growth while protecting the environment (Fig. 1). Chemical pollution has increased significantly as a result of the industrialization of agricultural practices (Samada & Tambunan 2020; Kumar 2014) [16, 27]. Agrochemicals, also called pesticides, are widely used in urban green spaces, agriculture, and health initiatives to protect people and plants from various diseases (Mishra *et al.* 2020) [18]. However, since these pesticides have been shown to have a range of harmful effects on both the environment and human health, their side effects may pose a serious risk to public health (Chaud *et al.* 2021) [7].

In response to the urgent need for a greener approach, numerous creative methods have been developed that incorporate sustainable practices and aim at food sovereignty, such as agrarian reforms and food production (Caron *et al.* 2018) [5]. The use of synthetic organic pesticides in agricultural pest control initiatives worldwide is often associated with environmental damage (Sanchez-Bayo 2012). Synthetic compounds have been the main cause of pesticide resistance and adverse effects on non-target species in recent years (Leskovac and Petrovic 2023) [17]. Fish, birds, humans, waterfalls and beneficial insects are severely harmed by these pesticides (Talebi *et al.* 2011) [33]. Promoting sustainable agricultural growth and protecting the environment from the harmful effects of chemical pesticides are the goals of the development and application of biopesticides (Marella & Prasad 2019).

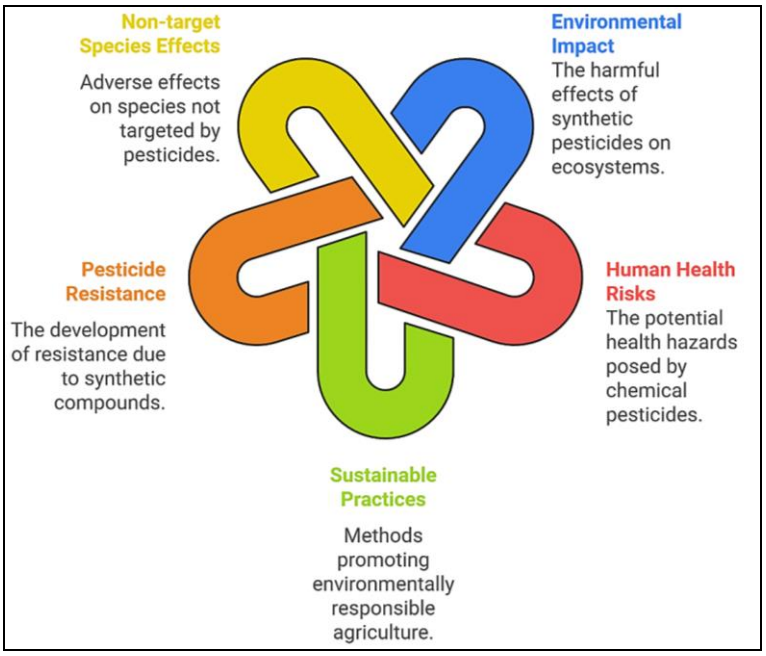

Fig 1: Pesticides sustainable in agriculture

Rise of biopesticides

The idea of sustainable agriculture is driven by growing awareness and concern about how agricultural practices impact the environment and the production of food and fiber. This means that biopesticides are becoming more important than synthetic pesticides (Fenibo *et al.* 2021) [11]. Problems such as environmental pollution from pesticides, post-harvest chemical consumption through bioaccumulation, loss of biodiversity and the emergence of secondary pests to eradicate natural/beneficial enemies are all results of the extensive use of conventional pesticides in industrial agriculture over a long period of time, particularly during the green revolution. These side effects are not related to the use of biopesticides (Ayilara *et al.* 2023) [4]. So, while the number of new conventional pesticides fell from 70 in 2000 to 28 in 2012, the number of active ingredients in conventional pesticides fell from over 1,000 in 2001 to just 250 in 2009 (Fenibo *et al.* 2021) [11]. The increased demand for biopesticides for certain positive reasons is a direct consequence of the decline in the use of traditional pesticides (Damalas and Koutroubas 2018) [8].

Challenges and opportunities

Unlike traditional chemical pesticides, despite their benefits, biopesticides are still rarely used in developing countries like India. Biopesticides face numerous obstacles at the local level, although the Indian government is trying to promote their use by incorporating them into numerous agricultural initiatives. What is worrying is that farmers are less flexible and less interested in biopesticides. Biopesticide regulations in the EU may change due to a greater focus on integrated pest management as part of agricultural policy (Chandler *et al.* 2011) [6]. The fusion of ecological science and post-genomics technologies also creates new perspectives for the development of biopesticides in IPM (Taning *et al.* 2021) [34].

Pesticides are detrimental to the natural world and are thus regarded as toxic to the environment (Murugesan *et al*., 2021) [21, 22]. Chemical pesticides, comprising herbicides, fungicides, rodenticides, and insecticides, pose a serious threat to biodiversity and the environment, contributing to air and water pollution (Murugesan *et al*., 2023) [20]. Many are turning to natural alternatives over synthetic counterparts in pursuit of safety and stability (Murugesan *et al*., 2021) [21, 22]. Traditional medicine is also a vital source of potentially valuable compounds for the development of therapeutic agents (Kaleeswaran *et al*., 2019) [15]. Plant extracts and secondary metabolites have emerged as promising alternatives to synthetic pesticides (Rengarajan *et al*., 2024) [25, 26], offering potential solutions for sustainable pest management strategies (Murugesan *et al*., 2024) [19].

Biopesticides

Various types of biopesticides have been developed to replace synthetic pesticides (Table 1). Microbial, biochemical and plant-integrated protectants are the three basic categories into which biopesticides can be broadly classified (AL-Ahmadi 2019) [1]. Insects, weeds, and plant diseases can all be controlled with microbial biopesticides made from microorganisms such as bacteria, fungi, and viruses (Hossain *et al.* 2017) [14]. Compared to synthetic pesticides, these biopesticides are often more targeted and less harmful than biochemical biopesticides, which are naturally occurring compounds that can be used to control pests by altering their physiology or behavior. Compared to synthetic pesticides, these biopesticides generally have a lower risk of bioaccumulation and are referred to as incorporated repellents (Fig. 2).

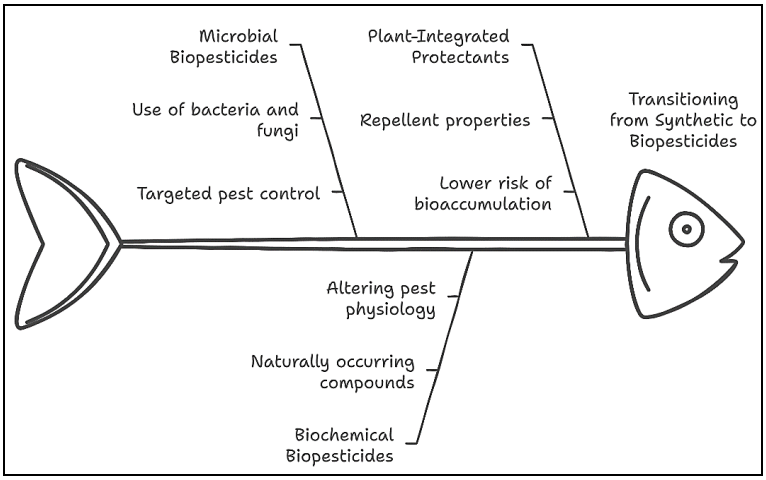

Fig 2: Understanding biopesticides in sustainable agriculture

Table 1: Different types of pesticides and mode of actions

S. No	Types of Pesticides	Mode of actions/ Target pest/ Functions	Examples of Chemicals
1.	Acaricides	Substances that kill or impair mite and tick growth. Pyridaben, etoxazole, spirodiclofen, and bifenazate are beneficially safe, low-mammal-toxic, and short-lived acaricides.	*Chlorinated hydrocarbons, Organo phosphorous, Carbamates, and* pyrethroids, *etc.*
2.	Algicide	To destroy algae and other aquatic vegetation	*Copper Sulphate, diuron, oxyfluorfen, etc.*
3.	Antifeedant	By an apparent ability to block the function of an herbivore's feeding stimulus receptors	*Alkaloid, flavonoid, and terpene*
4.	Avicides	Chemicals used to kill birds	*Strychnine, fenthion, etc*
5.	Bactericides	Used to describe drugs whose mechanism of action stops the cellular activity of bacteria without directly killing the bacterial.	*Streptomycin, tetracycline, etc*

6.	Bird repellents	Act as irritants or unpleasant flavors that induce an innate avoidance response in birds.	*Methyl anthranilate*
7.	Fungicides	Used to prevent or eliminate fungal infections in plants or seeds. Most fungicides have low to moderate toxicity.	*Alkyldithiocarbamic acid, ferbam, and mancozeb, etc.*
8.	Herbicides	Herbicides are used in agricultural and wildland ecosystems to reduce weed density and promote the growth of desirable species.	*Alachlor, paraquat, etc.*
9.	Insecticides	Chemicals that can be used to control insects by either killing them or preventing them from performing unwanted or harmful behaviors.	*Azadirachtin, DDT, etc.*
10.	*Larvicide*	A *larvicide* is a type of insecticide used to control mosquitoes inside and outside around your home.	*Methoprene*
11.	Molluscicides	Control of slugs in crops.	*Ferric phosphate* and Metaldehyde
12.	Nematicides	Action refers to the lethal effect of a nematicide on specific and vital life processes in the tissues of the nematode	*Methyl bromide and dichloropropene*
13.	Ovicides	Inhibit the growth of insects and mite eggs.	*Benzoxazin*
14.	Rodenticide	Rodenticide poisoning is common in all small animals. Rodenticides are often used around farmhouses to control rodents such as rats and mice that destroy property and farm produce.	*Zinc phosphide, strychnine*

Mechanisms of action

The way in which biopesticides work to minimize damage to non-target organisms and the environment while efficiently controlling pests. There are numerous ways in which biopesticides can work (Usta 2013) [35]. Certain biopesticides, such as those made from bacterial toxins, have the ability to directly kill or incapacitate their target pests, but others work more covertly to alter the physiology and behavior of the pests they harass changing life cycle. This could mean preventing the pests from feeding, reproducing or growing, or activating the target plants' natural defense mechanisms. In addition, biopesticides can work by strengthening plants' natural defenses or by attracting and maintaining populations of beneficial organisms that can either prey on or displace the target pests (Singh *et al.* 2019) [32].

Challenges and opportunities

The review also addresses the difficulties and opportunities associated with the production and use of biopesticides. One of the most difficult tasks is overcoming environmental obstacles such as temperature, humidity and UV rays, which can reduce the effectiveness and shelf life of biopesticides in the field. The development of nanotechnical delivery systems or the use of formulations that can better protect the biopesticides from environmental influences are two possible approaches to overcome these obstacles (Ghodake *et al.* 2018) [12]. Another difficulty is that target pests can develop comparable resistance to synthetic pesticides (Siegwart *et al.* 2015) [31]. Biopesticides should be used in conjunction with other pest control methods as part of integrated pest management. Despite these obstacles, there are numerous opportunities for further measures development and use of biopesticides, which have proven effective in pest control in many respects, could also lead to new developments in biopesticide regulation and lower barriers to entry for biopesticides in IPM (Chandler *et al.* 2011) [6].

Benefits of biopesticides

Comparing biopesticides to traditional chemical pesticides shows a number of advantages. According to Godake *et al.* (2018) they are better suited for targeted pest control and are safer for the environment. In general, biopesticides are less toxic and more environmentally friendly than synthetic pesticides because they come from natural sources such as bacteria, plants, animals and minerals (AL-Ahmadi 2019) [1]. Biopesticides, unlike chemical pesticides, are often more effective at lower doses, ensuring lower exposure and reducing the possibility of environmental contamination. In addition, biopesticides break down more quickly, which can increase crop yields and reduce the need for conventional pesticides (Seiber *et al.* 2014) [30]. However, biopesticides are not available without difficulty. Improving their performance is hampered by their intolerance to environmental factors such as temperature, humidity and sunlight. Furthermore, the use of biopesticides in developing countries like India is still minimal compared to traditional chemical pesticides, although the government is trying to limit or reduce the use to promote their use (Mishra *et al.* 2020) [18]. Concerns are raised and the need for solutions is highlighted by farmers' reduced adaptability and interest in biopesticides.

Challenges and limitations

The sensitivity of biopesticides to environmental factors such as temperature, humidity, and UV radiation can limit their effectiveness and persistence in the field, which is one of the main obstacles to their widespread adoption (Ghodake *et al.* 2018) [12]. To solve this problem, scientists are working to formulate and deliver nanoengineered delivery systems that better protect biopesticides from environmental damage. Another difficulty is that target pests may develop resistance, which could reduce the long-term effectiveness of biopesticides. Biopesticides should be used in conjunction with other pest control techniques as part of an integrated pest management strategy to reduce selection pressure for resistance. Biopesticides are safer for the environment and human health, have more targeted effects and, despite these disadvantages, can have a longer-lasting effect than synthetic pesticides. The review highlights the regulatory hurdles facing the biopesticide sector, as existing frameworks are often tailored to the evaluation of chemical pesticides rather than living organisms (Chandler *et al.* 2011) [6]. A stronger focus of agricultural policy in the European Union on integrated pest management could lead to new approaches to the regulation of biopesticides and lower barriers to market entry.

Case studies and success stories

Although only small amounts of biopesticides are still used in many regions of the world, there are a number of success

stories that illustrate their potential. By incorporating biopesticides into a number of agricultural initiatives, the Indian government has promoted the use of these pesticides. However, lower adaptability and declining interest among farmers pose problems for biopesticides at the local level (Mishra *et al.* 2020) [18]. To overcome these obstacles, scientists and policymakers should strive to develop more user-friendly and effective biopesticide formulations and educate farmers about the benefits of these environmentally friendly pest control options. A greater focus on integrated pest management in the EU has opened new avenues for the development and use of biopesticides. By integrating ecological science and post-genomic technologies, novel biopesticide products have been developed that are more suitable for IPM systems (Chandler *et al.* 2011) [6].

Future prospects and innovations

Despite its challenges, the biopesticide industry offers many exciting prospects for future development and innovation. The use of nanotechnological systems to improve the effectiveness and environmental stability of biopesticides is a promising area of research (Ghodake *et al.* 2018) [12]. Researchers can increase the effectiveness of biopesticides and protect them from environmental damage by encapsulating them in nanomaterials. Another example of innovation is the incorporation of biopesticides into integrated pest management systems. Researchers are developing new biopesticide products that are more suitable for integrated pest management (IPM) by combining ecological science with post-genomics technologies (Anderson *et al.* 2019) [3]. In agriculture and other sectors, the biopesticide industry is becoming increasingly important as the need for greener and more sustainable pest control solutions grows. The future of biopesticides seems bright as long as funding and innovation are maintained. They offer a viable replacement for traditional chemical pesticides and contribute to creating a more sustainable food system (Ayilara *et al.* 2023) [4].

Sustainable practices and biopesticides

Biopesticides provide a more environmentally friendly method of pest control and are an essential part of sustainable agriculture. The need to protect biodiversity and endangered species, as well as the growing demand for organic and residue-free foods, have all contributed to the growing interest in biopesticides (Samada and Tambunan 2020) [27]. To reduce reliance on synthetic pesticides, biopesticides are being incorporated into integrated pest management plans that include a variety of pest control techniques in many regions of the world. By incorporating biopesticides into integrated pest management (IPM) systems, it is possible to significantly reduce the negative environmental impact of agriculture while achieving high yields (Zalom 2010) [36]. In urban green spaces and public health initiatives, biopesticides can help control pests and diseases while minimizing risks to human health and the environment. This has been the subject of recent research (Kumar 2014) [16].

Economic and policy considerations

Political and economic difficulties are also associated with the development and use of biopesticides. Because biopesticides often involve living organisms rather than chemical compounds, the registration and regulation of these products can be more complicated than synthetic pesticides (Chandler *et al.* 2011) [6]. However, due to the increasing demand for environmentally friendly and sustainable pest control solutions, new market opportunities for biopesticides are emerging. The European Union's focus on IPM in agricultural policy has the potential to lead to novel approaches to regulating biopesticides that could reduce barriers to market entry (Glare *et al.* 2016) [13]. Through various agricultural programs and subsidies, governments in many developing countries actively promote the use of biopesticides (Kumar 2014) [16]. This demonstrates an understanding of the critical role that biopesticides can play in promoting food security and sustainable agricultural development.

There is an urgent need for cleaner and safer farming practices

The misuse and excessive use of pesticides have harmful effects on human and animal health and on the environment. The search for novel biopesticides that are safer for the environment, more selective and more effective in terms of toxicity is also driven by the increasing emergence of pesticide resistance. All life on Earth is exposed to dangerous agrochemicals through the contamination of food, air, soil and water with pesticides, which has led to chronic illnesses and even human deaths. Common arguments against the continued use of synthetic pesticides include negative health effects, environmental concerns and the growing demand for organically grown food. Given these obstacles, it is imperative to adopt more environmentally friendly and sustainable farming methods. The environmental and human health risks posed by indiscriminate pest control methods can be reduced by switching to integrated pest management, the use of biopesticides and biologically-based pesticides, and the introduction of strict laws banning the use of synthetic pesticides. By implementing these creative strategies, we can move towards a time where pesticides are viewed as tools that support resilient and sustainable food production in balance with the environment, rather than as enemies of the environment.

Conclusion

The environment and public health are being seriously harmed by the increasing industrialization of agriculture and the ubiquitous use of synthetic pesticides. In response, the development and application of biopesticides has become a viable option to support environmentally friendly agricultural practices and protect the environment. Despite the various technological, legal and financial hurdles that biopesticides must overcome, their potential is demonstrated by a number of creative solutions and success stories. To fully realize the benefits of biopesticides and accelerate the transition to a more sustainable food system, research, policymakers and industry must continue to invest in each other and collaborate.

Credit authorship contribution statement

Jayaseelan T: Writing – original draft.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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