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IMPLICATION OF BIOPESTICIDES FOR INSECT PEST MANAGEMENT: AN ALTERNATIVE OF CHEMICAL PESTICIDES

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ABSTRACT

The growing global concerns about ecological and health issues have raised the necessity of managing insect pests without the use of chemical pesticides. This fact has prompted to explore alternative methods of pest management that are efficient and environmentally sustainable. This review highlights the advancement of biopesticides, including their application with specificity to target pests as well as constraints and prospects with market status. Biopesticides, which are derived from natural sources such as plants, bacteria, fungi, and insects, provide a sustainable and environment friendly solution for controlling pests while minimizing harm to non-target organisms. The biopesticide market has been increasing globally, and thousands of commercially marketed biopesticides are now used against insect pests. Worldwide, most marketed biopesticides are derived from several subspecies of *Bacillus thuringiensis,* which control diversified orders of pests, including Lepidoptera and Diptera. Although, biopesticides have shown significant efficacy, restricted formulation approaches have limited their overall acceptance due to lower acute activity and a higher degradation rate. The review highlights the importance of ongoing research, development, and regulatory support for biopesticides to a large extent. Then, biopesticides have become a beacon of hope for a safer and more eco-friendly approach for controlling pests.

Keywords: Biopesticide, biopesticide market, eco-friendly management, microbial pesticide, pest management.

INTRODUCTION

Crop production has been facing an enormous challenge due to diverse pests and pathogens for a long time, which leads to a reduction in crop yield. Surprisingly, the annual loss of crop yield is around 20-40% globally because of plant damage caused by insects and phytopathogens (Sehrawat and Sindhu 2019). The global climate change scenario is a concerning new challenge for pest and disease management

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because it has been deflecting the temporal and geographical distribution of insects and pathogens. Over the last three decades, the unregulated and indiscriminate use of synthetic chemical pesticides to control pests and diseases has introduced several ecological and environmental issues such as negative impact on soil health, decline in water quality and wildlife habitat (Stehle and Schulz 2015). Besides, insect resistance and resurgence have been developed due to the continuous application of pesticides and fungicides in modern farming. The overuse of chemical pesticides can result in toxic pesticide residues in grain crops, vegetables, and cereals that are dangerous to human health. In addition to humans, non-target insects or beneficial organisms like pollinators, predators, parasitoids, and wild animals have also been affected by the adverse effects of pesticides. It was reported that honeybees and other insect pollinators had been reduced drastically due to overuse of chemical pesticides (Gill *et al*. 2012). Nevertheless, for ensuring food security for the increased world population, management of these pests and diseases is imperative, but it should be practiced without causing any damage to human health, public resources, and the environment (Chandler *et al*. 2011). These challenges, coupled with high costs of synthetic pesticides and consumer demand for organic food have generated the impetus to introduce and establish safe, effective, and biodegradable pesticide (Moshi and Matoju 2017). Biopesticides are considered a potential alternative to synthetic chemical pesticides. Nowadays, conventionally applied biopesticides have been used successfully in the field of agriculture and horticulture. Among the developed biopesticides, a considerable number have been marketed in the USA, Europe, Latin and South America, but fewer in Asia (Dutta 2015). The major consequences of using biopesticides are to reduce environmental damage and minimize human health hazards. There is a unique feature of biopesticide that it acts on specific target hosts (insects or pathogens) and reduces the risk of affecting beneficial insects, birds, mammals, and non-target organisms. Biological control of pests and diseases, including microorganisms or biopesticides is recognized as a pragmatic approach and observed a radical decrease of the adverse effects of agrochemicals in soil. The current strategy of Integrated Pest Management (IPM) and organic agriculture demands the inclusion of biopesticides to reduce reliance on chemical pesticides (Isman 2008). There are about 50 entomopathogenic agents that are being used commercially as microbial bio-pesticide (Morales-Ramos *et al.* 2013). The review examines the status of the potential use of biopesticides for pest and disease control, specifically for cereals, fruits, and vegetable crops. Considering all the opportunities, the review study was undertaken to compile the shortcomings and challenges for establishing biopesticide as a potential alternative to synthetic chemical pesticides, with a goal of producing safe food and a healthy environment.

BIOPESTICIDE FOR PEST MANAGEMENT

Almost 30 % reduction of agricultural yield is considered due to pests (Pandya 2018), and 14% of storage products are damaged due to these pests (Jankielsohn 2018). Improvement in the potential yield of crops and the protection of stored products requires a cautious application of pesticides and fertilizers. Bio-pesticides can be categorized as natural products or pesticides including active agents that can control the pests through non-toxic ways (biochemical pesticides), microorganisms and their products that can influence the population of pests and pesticidal effects produced by plants due to transgenic approaches (plant-incorporated protectants) (Ibrahim and Shawer 2014). Most biopesticides have multiple modes of action against the pests they are intended to control, which reduces the likelihood that the pests may evolve resistance (Hassan and Gokce 2014). Due to their benefits, biopesticides can be considered for integrated pest management (IPM) because of their effectiveness, biodegradability, and eco-friendliness (Marrone 2009).

MARKET STATUS OF BIOPESTICIDES

The annual rate of biopesticide use is rising by 10% globally (Kumar and Singh 2015). The market value of biopesticides had a growing trend over the last decade. Market value of biopesticide over the last 2 decades was analyzed with R programming environment (R Core Team 2021). However, significant different was observed with the market value of biopesticide during the period ($P<0.001$). In 2009, biopesticides accounted for $1.6 billion (3.5%) of the global pesticide market following a steady growth of $1.3 billion in 2011, $2.1 billion in 2012, and reached to $3.3 billion by 2014, with a compound annual growth (CAGR) of 15.6% during that period (Moosavi and Zare 2015, Markets and markets 2012). However, the market distracted a little from its raising trend in 2017 where the estimated value was $3.20 billion. The market recovered its growing trend and showed tremendous growth of $3.42 billion in 2019. The global biopesticide market was valued at approximately $4.0 billion in 2020 (Markets and Markets 2022, Research and Markets 2022). It is anticipated that the worldwide biopesticide industry will have expanded to $4.5 billion by 2023 (Olson 2015) and $4.62 billion in 2025 (Sinha *et al.* 2016, Markets and Markets 2022). Additionally, over the next five years (2023–2028), it is expected to expand at a compound annual growth rate (CAGR) of 11.7%, reaching $9.6 billion in 2028 (Globe News Wire 2022b) which is more than double with the current market value (Fig. 1). The development and manufacturing of bioinsecticides is a highly lucrative industry since the worldwide bioinsecticide market is expected to expand from an anticipated value of $5 billion today to $15 billion by 2029 (Marrone 2024).

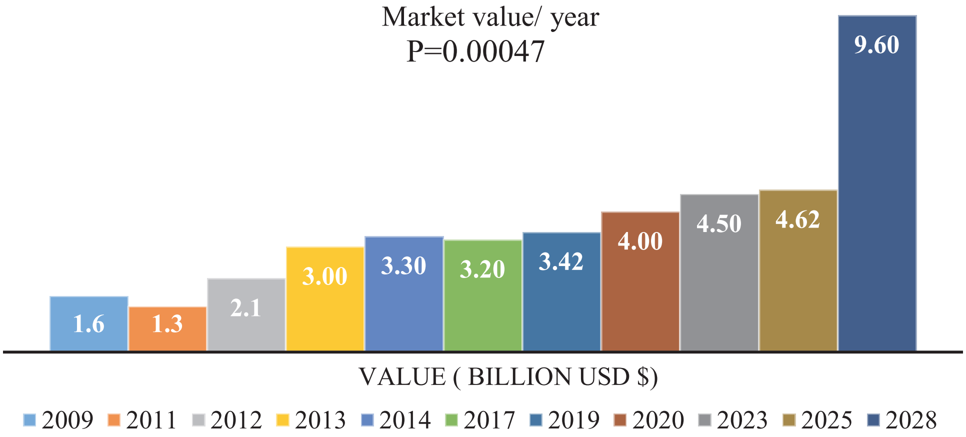

Fig. 1. Global market value (Billion US $) of biopesticide over past 15 years and the prediction for next 4 years (P<0.01). Sources: Moosavi and Zare 2015, Markets and markets 2012, Sinha *et al.* 2016, Olson 2015, Globe News Wire 2022b

According to Olson (2015), North America dominates the global biopesticides market, with Europe and Asia-Pacific coming in second and third. Globally, biopesticide markets was expanded at yearly rates of 45% in North America, 25% in Europe and Oceania, 15% in nations in Latin and South America, and 7% in Asia (Ramírez-Guzmán 2020). Europe accounts for 19% of the market with a CAGR of 15.02%, the market is projected to increase from $1.31 billion in 2021 to $3.71 billion in 2026 (Market Data Forecast 2022). According to Singh and Mazumdar (2022), the European market is predicted to grow at one of the fastest rates worldwide. In terms of biopesticide manufacturing, Europe is the second-largest producer of biopesticides, having 60 biopesticide products compared to North America that produces about 200 products (Kumar *et al.* 2021). The market for biopesticides worldwide is dominated by bioinsecticides (Markets and Markets 2022). Bioinsecticides (47%) had the most market share of all biopesticides in 2020, according to the AGROW research on biopesticides projects in 2019, followed by bio-fungicides, bionematicides, bioherbicides, and others (Butu *et al.* 2022) (Fig. 2).

Pheromones, plant extracts, and plant growth regulators are examples of biochemicals that currently make up the largest category of biocontrol agents, but microbial biopesticides will be about equal in importance by 2029 (Marrone 2024). The microbial biopesticide market is dominated by North America and Latin America. Due to an extensive record of using plant extracts and plant growth regulators, the Asian market uses biochemicals more frequently than any other region. However, due to regulatory measures that prevent the introduction of microorganisms, the European Union market presented a lower amount of microbial share. Over the last two decades, Europe shared 20% of the total biopesticide market and the position was after North America (44%) (Kabaluk *et al.* 2010, Marrone 2024). As of August 2022, there were 567 registered biopesticides. Among them, 60.4% were microbials, 13% were pheromones, 9% were other biochemicals, and the remaining were macro-organisms (Pucci 2022). Despite their global market value of approximately $3 billion, biopesticides only make up a small 5% of the entire crop protection industry (Marrone 2014, Olson 2015). Aaccording to Marrone (2007), approximately 1,400 biopesticides products have been sold globally. Bacteria-based products are the leading products in the industry worldwide (Lehr 2010). The primary bacteria utilized in agricultural pest control were *B*acillus thuringiensis (Bt) (Ali *et al*. 2008). About two hundred Bt-based products account for more than 53 % of the global biopesticide market (CABI 2010).

The European Union registered 68 biopesticides active compounds including 34 microbials, 11 biochemicals and 23 semiochemicals (EUPD 2010). Chandler *et al.* (2008) reported that the UK had only 5 microbial biopesticides available, while Germany had 10 and both France and the Netherlands had 15. Spain is the top biopesticide market in Europe in terms of value, followed closely by Italy and France (Business Wire 2010). There were 327 biopesticides registered in China as of 2008. There are 35 registered viral biopesticides derived from *Heliothis armigera* and Nuclear Polyhedrosis Virus (NPV), 22 registered fungal biopesticides manufactured from 6 fungal species, and 270 registered bacterial biopesticides developed from 11 microbial species (mostly Bt) (ICAMA 2008). About 40% of the market in Latin America is made up of items containing Bt (CPL Business Consultants 2010). Brazil has been a leader in the use of biopesticides; by 2010, microbial pesticides were applied to over 3 million hectares of agriculture annually (Kabaluk *et al.* 2010). EPA statistics showed that 102 microorganisms, 52 biochemicals, and 48 semiochemicals used as biopesticides in the USA (USEPA 2011). In India, at least 15 microbial control agents with 970 commercially registered formulations had been produced as biopesticides as of 2017 (NBAIR 2017).

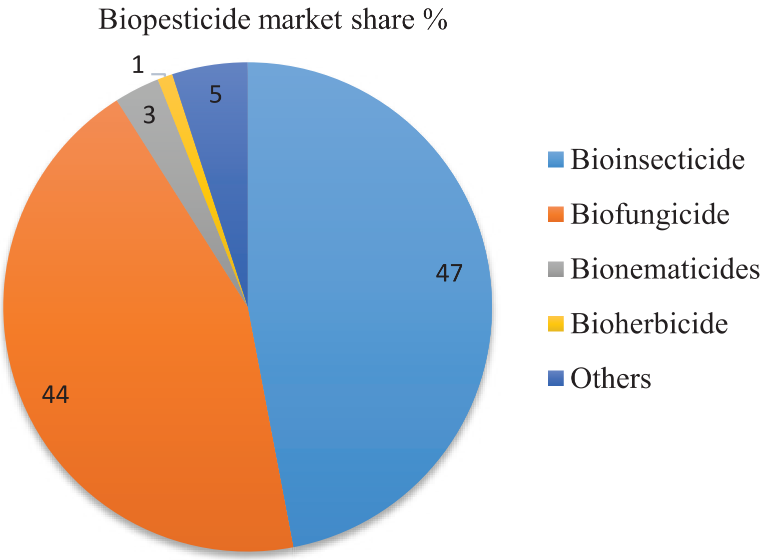

Fig. 2. Global market share (%) for different types of biopesticide in 2019. Source: Butu *et al.* 2022

APPLICATION OF BIOPESTICIDE FOR PEST MANAGEMENT

Biopesticides are a long-term, environmentally sound method of managing pests that are excellent tool for Integrated Pest Management (IPM) (Sarwar 2015). Biopesticides are used globally to treat insect pests and are generated from microorganisms (bacteria, fungi, viruses, etc.), plants, animal products (pheromones, hormones, insect-specific toxins, etc.), and genetically modified organisms (Islam and Omar 2012). Thus, over the past few years, biopesticides have gained international attention as a safer approach to pest management (Arora *et al.* 2016). Mammalian toxicity to most biopesticides may range from mild to considerable. In the field, they are less hazardous to beneficial insects and sometimes more selective for pest insects that feed on plants due to their quick degradation and stomach poisoning properties (Ahmad *et al.* 2011). Bio-pesticides are widely used to control insect pests and are divided into different categories depending on their source of origin. Following is the list of biopesticides used broadly to control many insect pests (Tables 1-5).

Table 1. List of entomopathogenic bacteria used as biopesticides for pest control over the years

Common names	Target insects
Entomopathogenic bacteria	
Bacillus thuringiensis israelensis (Bti)	Diptera: flies and mosquitoes
B. sphaericus	Diptera: flies and mosquitoes
B. thuringiensis sub-species *japonensis*	Coleoptera: Scarabaeidae, soil inhibiting beetle
B. thuringiensis sub-species *aizawaia*	Lepidopteran pest (Gypsy moth, tent caterpillar and cabbage looper)
B. thuringiensis sub-species *kurstakia*	Lepidopteran pest: Caterpillars of cabbage worms, diamondback moth, leaf rollers, maize borers
B. thuringiensis sub-species *galleriae*	Lepidopteran larvae, Colorado potato beetle
B. thuringiensis sub-species *tenebrionis*	Colorado potato beetle
Paenibacillus popilliae	Coleoptera: Scarabaeidae
Serratia entomolphila	Grass grub
Bacillus moritai	Dipteran pests
Burkholderia spp.	Chewing and sucking insects, mites, nematodes

Sources: Rajput *et al.* 2020, Kabaluk *et al.* 2010, Mashtoly *et al.* 2010, 2011, Shishir *et al.* 2012, Jurat-Fuentes and Jackson 2012, Koppenhofer *et al.* 2012, Johnson *et al.* 2001, Ruiu 2018

Table 2. List of entomopathogenic fungus used as biopesticides for pest control over the years

Common name	Target insects
Entomopathogenic fungi	
Paecilomyces fumosoroseus, Isaria fumosoroseus	Spider mite (*Tetranychus cinnabarinus*); White flies
Aschersonia aleyrodis	Hemiptera (Whitefly)
Conidiobolus thromboides Acari	Hemiptera (Whitefly), Thysanoptera (Thrips)
Beauveria brongniartii	Coleoptera (Scarabaeidae)
Metarhizium anisopliae	Termite, Locust, Grasshoppers, *Aedes aegypti* and *A. albopictus* mosquitoes;
Metarhizium anisopliae sensu lato	Coleoptera (Rhinoceros beetle), Hemiptera (Locust, Grasshoppers), Isoptera (Termite)
Nomuraea rileyi	Soybean: Spodoptera litura, *Helicoverpa armigera, Thysonoplusia orichalcea* Lepidoptera
Beauveria bassiana with Neem	*Bemisia tabaci* (Gennadius) (Sweet potato whitefly, Cotton whitefly)
Neozygites floridana	*Mononychellus tanajoa* (Bondar) (Casava green mite), *Tetranychus evansi* (Tomato Red Spider mite)

Sources: Shi and Feng 2004, Lacey *et al.* 2011, Hajek *et al.* 2012, Townsend *et al.* 2010, Scholte *et al.* 2007**,** Thakre *et al.* 2011, Islam *et al*. 2010, Duarte *et al*. 2009

Table 3. List of entomopathogenic viruses used as biopesticides for pest control over the years.

Common name	Target insects
Entomopathogenic virus	
Granulosis Virus (GV)	Oriental fruit moth, codling moth (*Cydia pomonella)*
Diamond back moth GV	*Plutella xylostella*
Cotton bollworm NPV (HearNPV)	Cotton bollworm (*Helicoverpa armigera*), pod borer
Corn earworm NPV (HezeSNPV)	Corn earworm *(Helicoverpa zea*), tomato fruit worm, tobacco budworm (*Helioth virescens)*
Alfalfa looper NPV (AucaMNPV)	Noctuidae
Tea moth (BuzuNPV)	Tea looper (*Buzura suppressaria*)
Velvetbean caterpillar NPV (AngeMNPV)	Velvet bean caterpillar *(Anticarsia gemmatalis)*

Sources: Yang *et al.* 2012, Arthurs and Lacey 2004, Rowley *et al.* 2011, Kabaluk *et al*. 2010, Panazzi 2013

Table 4. List of entomopathogenic nematodes and protozoa used as biopesticides for pest control over the years

Common name	Target insects
Entomopathogenic nematodes and protozoa	
Heterorhabditis bacteriophora	White grubs (scarabs), cutworms, black vine weevil, flea beetles, corn root worm, citrus root weevils (*Diaprepes* spp.)
Heterorhabditis megidis	Weevils
Heterorhabditis indica	Fungus gnats, root mealybug, grubs
Heterorhabditis marelatus	White grubs (scarabs), cutworms, black vine weevil
Heterorhabditis zealandica	Scarab grubs
Steinernema glaseri	White grubs (scarabs, especially Japanese beetle, *Popillia* spp.), banana root borer
S. kraussei	Black vine weevil (*Otiorhynchus sulcatus)*

Common name	Target insects
S. carpocapsae	Turf grass pests-billbugs, cutworms, armyworms, chinch bugs, crane flies. Codling moth, banana moth, cranberry girdler, dogwood borer, black vine weevil, peach tree borer, shore flies (*Scatella* spp.)
S. feltiae	Fungus gnats (*Bradysia* spp.), shore flies, western flower thrips
S. scapterisci	Mole crickets (*Scapteriscus* spp.)
S. riobrave	Citrus root weevils (*Diaprepes* spp.), mole crickets.
Nosema locustae	Grasshopper, caterpillars, corn borers, and crickets
Vairimorpha spp.	Caterpillars

Sources: Campos-Herrera *et al.* 2012, Tofangsazi *et al.* 2015, Zhang and Lecoq 2021

Table 5. List of Plant Incorporated Protectants (Transgenic Plants) has been used as biopesticides for pest control over the years.

Common name	Target insects
Transgenic Plants	
B. thuringiensis Cry1A.105 and *B. thuringiensis* Cry2Ab2	Soybeans Lepidopteran pest
Bt Maize (Cry1Ab protein, Cry1Ac or the Cry9C protein	*Ostrinia nubilalis* Hubner (Corn borer)
Hybrid Corn with Cry3Bb1 protein	*Diabrotica spp* (Corn rootworm complex)
Cotton with Cry1Ac protein	*Helicoverpa zea* (Cotton bollworm)
Potato expressing the Cry3A or Cry3C, Cry4 proteins	*Leptinotarsa decemlineata* (Potato beetle), *Lycoriella castanescens* (Flies), *Culex pipiens* (Mosquitoes)

Sources: Chen *et al.* 2021, Icoz *et al*. 2008

CONTROVERSY AND CONSTRAINTS OF BIOPESTICIDE APPLICATION

Compared to synthetic pesticides, biopesticides have limitations in their widespread usage due to their lower acute activity, higher degradation rate, manufacturing complexity, poor investment performance, limited formulation options, regulations, and unfavorable prior performance histories (Glare *et al.* 2016). The inability to fully implement biopesticides due to various factors such as lack of availability of products to meet farmer demands, high cost of refined products, slow action, sensitivity to environmental changes, difficulty in determining active ingredients doses, short-lived stability, and variations in standard preparation techniques and guidelines (Fenibo *et al.* 2021). The lack of regulations in many countries prevents biopesticides from being sold (Arora *et al.* 2016). The main challenges in the development and implementation of novel biopesticides are related to marketing and promotion strategies, as well as enhancing the products' stability and residual effects (Damalas and Koutroubas 2018). Lack of confidence in the application of biopesticides was found to be one of the main reasons (Arora *et al.* 2010). Biopesticide-related agribusiness demands a significant financial commitment, significant risk, and minimal reward (Leng *et al.* 2011). It is important to understand the compatibility of biopesticides because some may have negative effects on natural enemies (predators and parasitoids) or each other (Seiedy *et al.* 2015).

Due to their limited availability and sometimes highly focused nature, some biopesticides are viewed as disadvantageous compared to treatments with broad-spectrum activity (Glare *et al.* 2012). Other barriers include a small market, rising competition from synthetic pesticides and the high cost of producing and registering a new biopesticide product (Lengai and Muthomi 2018). Ashaolu *et al.* (2022) state that the lack of consumer interest and rising market costs make it difficult to establish biopesticides profitable and marketable. However, there are still numerous obstacles in the way of the development, production, and application of biopesticides. To enable the commercialization of biopesticides, further research in biopesticide production, delivery, and formulation, as well as further funding for public sponsored initiatives, commercial investors, and pesticide companies are required (Kumar and Singh 2015).

PROSPECTS OF BIOPESTICIDE

Biopesticides are gaining attention on a global scale as a safer tactic because they pose less risk to humans and the environment. In fact, biopesticides are gradually replacing synthetic and traditional pesticides (Rani *et al*. 2021). Unlike chemical pesticides which can be detrimental to human health, the environment, and the life of other organisms (Samada and Tambunan 2020). Biopesticides are a great alternative to traditional pesticides as they are biodegradable and do not persist in the environment for a long period. They are easy to use and provide effective control of pests. With biopesticides, the use of traditional pesticides can be reduced, and they can be a key component of integrated pest management systems (Ruiu 2018, Kumar *et al*. 2021). Biopesticides are a safer alternative to chemical pesticides for farmers who want to protect their plant crops. They have a low risk of harming the environment and mammals, are species selective (i.e., safe for non-target creatures like honeybees), and have a low risk of developing resistance. Additionally, they are less likely to contaminate groundwater (Haddi *et al*. 2020). Biopesticides have been increasingly popular in recent years due to their effective application in sustainable agricultural practices (Gonçalves 2021). The use of synthetic pesticides has been declining annually by 2%, while biopesticides have seen an increase of 10%, due to their effectiveness in combating insect resistance and the implementation of integrated pest management techniques. Additionally, the ban on synthetic pesticides in certain areas has contributed to the shift towards biopesticides as an alternative agrochemical (Fenibo *et al.* 2021).

Biopesticides include a wide range of microbial pesticides, biochemicals obtained from microbes and other natural sources, and techniques involving genetically modifying plants to express genes encoding insecticidal toxins (Salma 2011). They have been used all over the world and have proven to be effective at managing pests. There is new potential in the European Union for the development of biological pesticides in conjunction with ecological research, post-genomic technologies, and integrated pest management (Chandler *et al.* 2011). The increasing demand for a safer food supply and the growing global concerns about pesticidal toxicity has become strong driving forces for the growth of the bioinsecticides market. Increasing numbers of countries, particularly economically developed countries, have been highly supportive of the adoption of bioinsecticides through imposing laws and policies, but the regulatory demands have increased in many jurisdictions, impeding the widespread adoption of bioinsecticides (Vekemans and Marchand 2020). Utilizing plant products as biopesticides has gained more interest in several regions across the globe. Nowadays, neem-based products, essential oils, and various secondary metabolites are used worldwide as botanical insecticides (Isman 2020). Further research is necessary particularly in the field, to determine how well botanical insecticides work along with traditional microbial and mineral-based pesticides. Similarly, one could control virus attacks on plants via genetically engineered species resistant to the virus (Williams *et al.* 2017).

There is a global trend toward the use of biopesticides instead of conventional pesticides; the size of the global biopesticide market was over USD 4 billion at the beginning of this decade and is projected to double by 2025, with bioinsecticides accounting for almost half of the overall biopesticide share (Rakshit *et al.* 2021). The development of biopesticides is currently expanding quickly in China and novel formulations of biopesticides such as Ningnanmycin, Shenqinmycin and Atailing etc. are being introduced (Liao 2020). However, Research & Development efforts, infrastructure, human resources, and a cooperative strategy from small, medium, and large businesses will be necessary for the effective development of biopesticides to guarantee that the products created have the potential to be commercialized (Glare *et al.* 2012).

The goal of current biopesticide research is to enhance their action spectrum and discover new ways to substitute chemical pesticides in integrated pest management strategies (Nawaz *et al*. 2016). The use of biopesticides in IPM programs can help mitigate the drawbacks of chemical insecticides, which have several significant benefits like being primarily host-specific, biodegradable, self-perpetuating, less hazardous to beneficial pests, and having a short shelf life (Matyjaszczyk 2015). The impact of Integrated Pest Management (IPM) policies in the European Union encourages the employment of novel pest management techniques, particularly the use of biopesticides, which are natural products or living microorganisms (Chandler *et al*. 2011). New products may be a potential solution for controlling pests, but more fieldwork is needed to determine which insect problems work best in different farming systems. As previously indicated, techniques focused on nanotechnology may enhance the residual efficacy of biopesticides, hence expanding their application in the field (Damalas and Koutroubas 2018).

CONCLUSION

Present review revealed that biopesticides have shown significant efficacy in combating insect pests while causing minimal harm to the environment, human health, and biodiversity. However, it is essential to consider that the use of biopesticides requires appropriate application techniques, and compatibility with integrated pest management strategies. Continuous research, development, and collaboration among scientists, farmers, and policymakers will be crucial in realizing the full potential of biopesticides as a cornerstone of sustainable pest management systems.

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