agriculture

*Review*

# Biopesticide Consumption in India: Insights into the Current Trends

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**Abstract:** Biopesticides are formulations derived from naturally occurring compounds that manage pests through non-toxic and environmentally favorable means. Being living organisms (natural enemies) or products, biopesticides represent less of a risk to the environment and to human health. Biopesticides, classified into three broad classes, are increasingly used in pest control, and include semiochemicals, plant-incorporated protectants (PIPs), and compounds derived from plants and microorganisms. Because of their advantages for the environment, target-specificity, efficacy, biodegradability, and applicability in integrated pest management (IPM) programs, biopesticides are gaining interest. Although biopesticides have seen significant advances in market penetration, they still make up a relatively small fraction of pest management solutions. Over 3000 tons are produced globally per annum, and this number is rising rapidly. In India, biopesticides account for just 4.2% of the country's total pesticide market. Although the government has promoted the use of biopesticides by including them in several agricultural programs, biopesticides face numerous difficulties at a local level, but are predicted to expand at an astonishing 10% yearly pace. Under the Insecticides Act 1968, the Ministry of Agriculture in India controls the use of pesticides. Among the major biopesticides produced and used in India are *Trichoderma*, *Bacillus thuringiensis*, nuclear polyhedrosis virus, and neem-based pesticides.

**Keywords:** *Bacillus thuringiensis*; microbial biopesticides; sustainable agriculture; plant protection; South-Asian agriculture



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## 1. Introduction

Pesticides are the natural or manmade substances that are primarily used to eliminate weeds, pests, insects, and disease-causing pathogens in plants in the agricultural fields. Some examples include insecticides, herbicides, fungicides, nematicides, and rodenticides. The rates of pest-caused loss of crops have been noticed to be quite high in both developing as well as developed countries [1]. The key elements of biopesticide management are a reduced crop loss and strong management of weeds and diseases. The random use of chemical pesticides has affected human health in a destructive manner over the years. According to the recent estimation by the World Health Organization (WHO), each year, around 25 million people suffer from acute occupational pesticide poisoning in developing countries, and, moreover, almost 20,000 people die worldwide. Among all of the other group of pests, insect pests cause major damages in agriculture. Therefore, it is very important to control such insect pests in order to enhance agricultural production.

In a broader perspective, approximately 70,000 pest species, including 9000 sporadic insect species, spoil agricultural crops around the world. One thousand insect pests are known to be major pests around the globe, and, among them, 200 insect species are considered as serious pests along with their economic importance in India [2,3]. In the entire process of agricultural development, the role of biopesticides has played an essential role in providing plant protection and improving the quality and productivity of crops [4]. A biopesticide is a constitution of natural substances used to regulate non-toxic mechanisms of pests in an ecological way. The sources of biopesticides can be plants, animals, and even microorganisms that are specifically used for the management of harmful organisms [5]. However, sometimes biopesticides may cause a small risk to the environment and human health. Generally, they are less hazardous compared to chemical pesticides and best suited for organic farming. In microbial pesticides, each active microbial component is comparatively specific to its target pest mostly, but, in some cases, microbial pesticides can manipulate many different types of pests. For instance, *Bacillus thuringiensis*, commonly abbreviated as Bt, is a bacterium that manufactures crystalline proteins and destroys one or some relatable insect species specifically [6]. The target insect species is dependent on the binding of Bt crystal protein to the intestinal insect receptor. Unlike the chemical pesticides, the biopesticides are made of natural substances that are able to control the pests with the help of their non-toxic mechanisms. A few such examples are the sex pheromones of insects, some vegetable oils, and several aromatic extracts used to trap the insect pests [7].

Biopesticides are biodegradable, action-specific, and can respond to chemical-pesticide-mediated pest resistance issues [8]. Sustainable agriculture driven by biopesticides enhances social adequacy and economic productivity and provokes environmental protection. All three dimensions together constitute the tripartite concept of sustainable development. Biopesticides have great authority in sustainable agricultural management due to their satisfying characteristics of controlling both the green chemistry principles (GC principles) and the tripartite concept of sustainable development [9]. In recent years, biopesticides have grown in popularity and are thought to be more safe than conventional pesticides. Biopesticides are more focused on the target pests and, by their very nature, are less harmful than traditional pesticides. Biopesticides can also be used sparingly and are rapid to disintegrate without leaving any unfavorable residues, which could lessen the need for conventional pesticides in integrated pest management (IPM programs) [10].

Since it is a topical issue of interest in the domains of agriculture and sustainable development, there is a plethora of information available for this review. Google Scholar was used to acquire a preliminary sample of the types of various available articles. With regard to Google Scholar, wide search phrases were first utilized to compile a list of primary source and peer-reviewed papers. This was accomplished based on a variety of essential keywords, including biopesticide categories, the global market, biopesticide production and consumption, and legislative framework. The papers and research materials from Google Scholar were used as the foundation for the authors' use of a better list of more exact words for gaining access from other databases. The databases Scopus, ScienceDirect, and PubMed have also been used by authors. Second, to find further articles, the references part of each article was browsed through. A large percentage of the cited references were published during the last six years. A few studies from earlier decades were nevertheless included to lay the groundwork for notions that are still relevant today. The sources were analyzed using a variety of criteria, most of which were based on the following factors: the study's year, the reliability of the data collection, the study's area of focus, and the effects of the use of biopesticides. Nonetheless, the source had to be consistent with the objectives of the literature review based on the article's queries. For the quantitative portions, the authors searched for data gathered over a longer period of time and production and consumption patterns with some degree of variation in terms of category and application both globally and in India. In the case of qualitative data, the authors also assessed if the material has been used in other studies and whether it is based on earlier studies that have been undertaken. In this review, we focused on the global market, categories, and regulation of biopesticides, their production, consumption, and usage pattern in India, technological advancements in enhancing biopesticide efficacy, the usage of biopesticide as a contributor to agriculture and sustainable development, their limitations, and, lastly, the future prospects.

## 2. Global Market of Biopesticides

Currently, the USD 56 billion worldwide pesticide market is anticipated to have a biopesticide market of between USD 3 and 4 billion [11]. With compound annual growth rates of 14.1% [12], it is estimated that the development of biopesticides will outpace that of chemical pesticides [11].

The US biopesticides market is now estimated at roughly USD 205 million, with a predicted increase to nearly USD 300 million by the end of the decade. North America consumes approximately 40% of the world's biopesticide production. The market for European biopesticides was predicted to be worth over USD 135 million in 2005 and reached approximately USD 270 million by 2010, with Oceanic and European countries accounting for 20% of global sales, respectively [13], as depicted in Figure 1. Sales of chemical pesticides are anticipated to decrease, whereas sales of biopesticides are predicted to expand moderately in South and Latin America, which, together, account for 10% of the global biopesticide market. As the mega-economies of China and India increase their usage of biopesticides, the Asian market—while still relatively small—presents a significant opportunity for biopesticides. According to India's agricultural ministry, biopesticides currently account for only 2.89% of the 100,000 metric tons of pesticides sold worldwide, but are expected to grow by an estimated 2.3% annually [13].

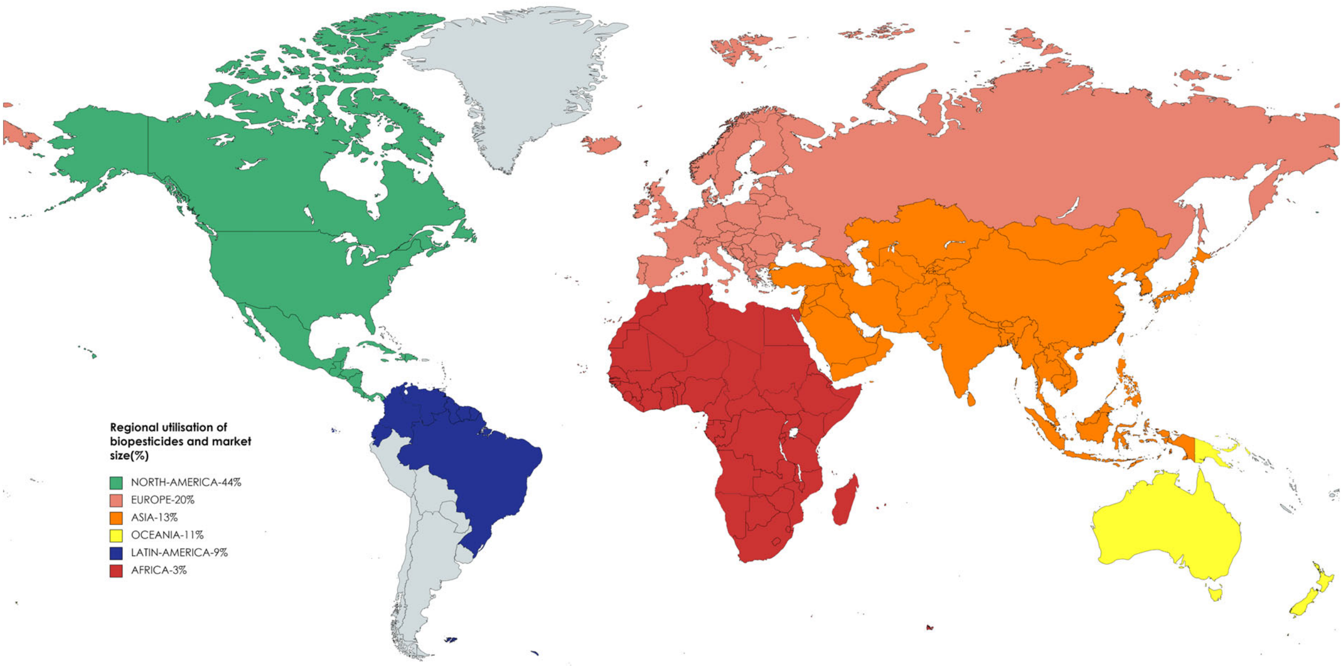


**Figure 1.** Global market and use of biopesticides.

There are more than 200 items accessible on the US (United States) market and 60 comparable products on the EU (European Union) market. Fewer biopesticides have been registered in the European Union than in Brazil, the United States, China, and India due to their extremely drawn-out and challenging registration procedures [14]. Only five microbial products were reported to be sold in the UK compared to ten in Germany and fifteen in each of France and the Netherlands [15]. In Nigeria, the minimal utilization of biopesticides is a consequence of poor infrastructure, expensive costs, and governmental policies. A total of 327 biopesticides were registered in China. A total of 11 species of microorganisms were used to create 270 bacterial biopesticides, of which, *B. thuringiensis* was used to create 181 biopesticides [16]. In Kenya, out of 868 registered products, 20 microbial pesticides are authorized for use. The list includes one baculovirus, nine entomopathogenic-fungi-based products, nine products based on *Bacillus thuringiensis*, and one product based on an entomopathogenic nematode [17].

Bacterial products, particularly those from Bt, are increasingly commonly employed. The biopesticide sector has traditionally placed a high priority on the production of Bt, which is currently the primary bacterium used to control agricultural pests. Its strong position in the biopesticide sector is demonstrated by the fact that, according to the Centre for Agriculture and Bioscience International (CABI 2010), 200 Bt-based products occupy more than 53% of the global biopesticide market, with the USA and Canada consuming approximately 50% of this total [15]. *Bacillus thuringiensis*, which accounts for over 70% of all bacterial biopesticide use, is followed by *B. subtilis* and *B. fluorescens*. In addition to bacterial insecticides, fungi are now being employed as pesticides. Approximately 60% of the market for fungal biopesticides is made up of *Beauveria* species, and 60% of the market for viral biopesticides is made up of nucleopolyhedrosis virus. In general, smaller farms are more likely to use predator and virus biopesticides. Nematodes hold the largest market share (approximately 60%) among the "other" class of biopesticides [18].

By 2023, biopesticides were estimated to expand at an average annual rate of 8.64% and make up more than 7% (USD 4.5 billion) of the global crop protection industry [19]. In terms of market size, biopesticides are anticipated to catch up to synthetics between the late 2040s and the early 2050s, but there are significant uncertainties surrounding the uptake rates, particularly in regions such as Africa and Southeast Asia, which account for a large portion of the projections' flexibility [12].

Although the usage of biopesticides is rising by approximately 10% annually on a global basis, it appears that the industry will need to expand even more in the future if these pesticides are to play a significant part in replacing chemical pesticides and eliminating the existing over-reliance on them [20]. Future market growth for biopesticides is closely correlated with biological control agent research. In order to improve the cooperation of businesses and research institutes on this problem, several scientists from various research institutes have conducted some studies. The agriculture industry can and should profit from the coexistence of biopesticides and chemical pesticides as it appears that biopesticides cannot yet totally replace chemical pesticides. In this context, it is envisioned that large-scale industrial development will be facilitated by speeding up the practical application of research findings [10].

## 3. Categories of Biopesticides

The US Environmental Protection Agency (EPA) has identified three main categories for biopesticides as summarized in Figure 2.

(1) Microbial biopesticides—Microorganisms (bacteria, fungi, viruses, protozoans, or nematodes) are the main component of microbial pesticides. Although each individual active ingredient in microbial pesticides is quite specialized for its intended pest(s), they can control a wide variety of pests [21]. These biopesticide classes have been effective in reducing weeds, plant diseases, and insect pests [22]. Microbial biopesticides can be applied to crops in a variety of ways, including as live organisms, dead organisms, and spores [8]. Microbial pesticides work to reduce disease by producing a toxin that is particular to the pest that is being controlled. The effect of microbial infections is brought about by the pathogen's infiltration through the skin or stomach of the insect, which leads to pathogen proliferation and the host's, i.e., insect's, death. The microbial pathogens generate insecticidal toxins that are crucial in their pathogenesis. Although their structure and toxicity might vary greatly, the majority of toxins generated by microbial infections are known to be peptides [21]; for example, *Verticillium leconi, Metarhizium anisopliae, Bacillus thuringiensis*, etc. Baculoviruses have a good prospect for the management of pests belonging to the orders Lepidoptera (butterflies and moths), Hymenoptera (sawflies), and Coleopteran (beetles). Chemical insecticides can be replaced with microbial pesticides since they are more effective. The insect pathogenic bacterium *B. thuringiensis* is the most commonly used microbial biopesticide (Bt). When bacterial spores develop, a protein crystal known as the Bt-endotoxin is produced. When ingested by insects that are vulnerable, this substance can lead to the lysis of gut cells [22]. The target insect species is determined by

the Bt crystalline protein's binding to the insect gut receptor [23]. Depending on the species, they are more or less pathogenic to the target pest [24].

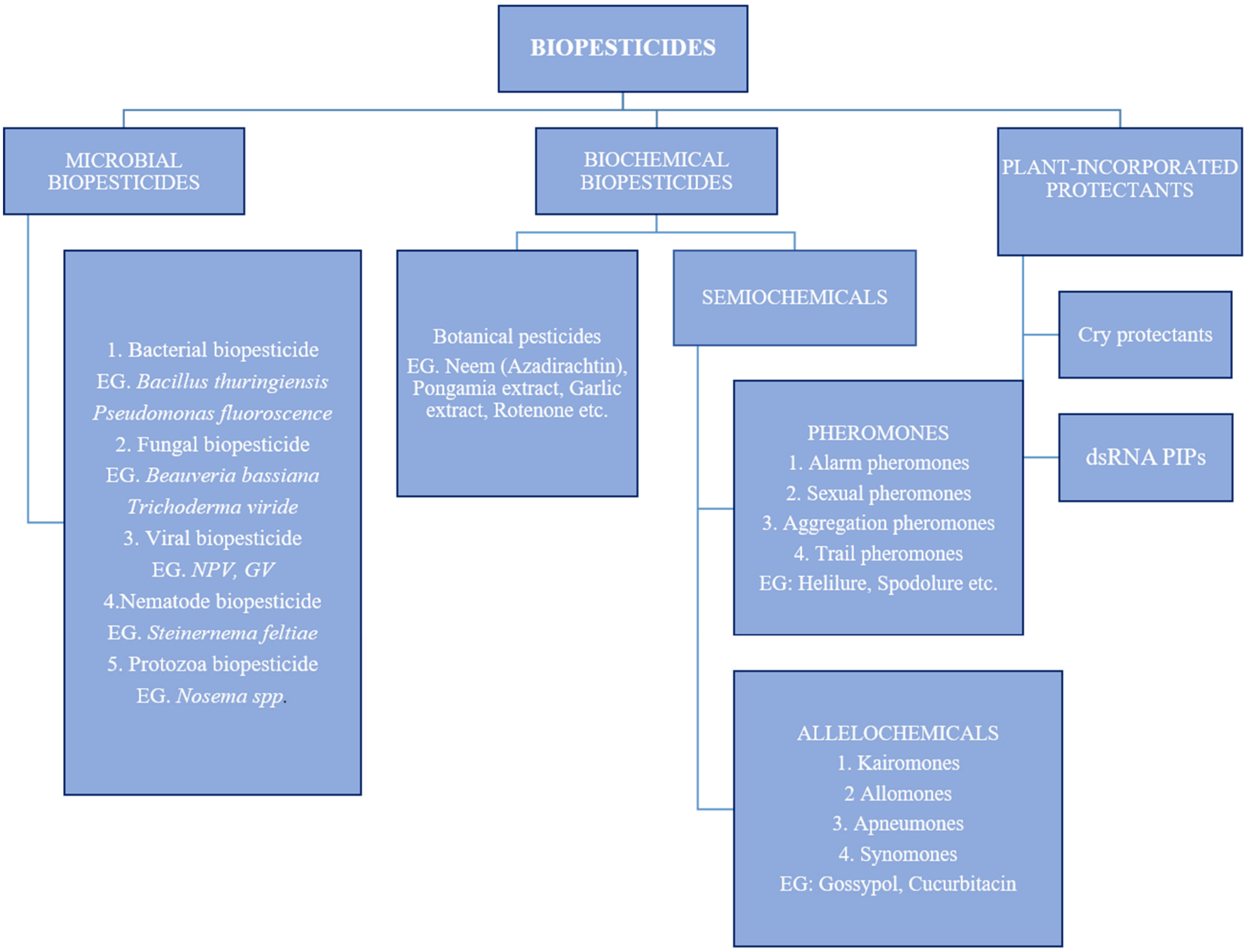


**Figure 2.** The three categories of biopesticides with examples.

(2) Biochemical pesticides—Biochemical pesticides are organic compounds that use non-toxic methods to control pests. These are employed to modify an insect's physiology, behavior, and even control [24]. Semiochemicals are also included in this group of biopesticides [25]. They might come from insects, animals, or plants. These categories of biopesticides include compounds such as plant growth regulators that prevent breeding and population expansion, as well as compounds such as pheromones that either repel or attract pests. When signals intended to cause a behavioral response are instead delivered to another organism, control becomes apparent [26]. The fast-acting insecticidal chemicals pyrethrins, which are generated by *Chrysanthemum cinerariaefolium*, are a common example of secondary metabolites that plants make to prevent herbivores from feeding on them [27]. Neem (*Azadirachta indica*) oil, an insecticide derived from the seeds of the neem tree, is the most popular botanical substance. At least two insect-killing chemical substances, azadirachtin and salannin, are produced by the neem tree. Azadirachtin inhibits insect feeding and controls growth [22].

(3) Plant-incorporated protectants (PIPs)—PIPs are biopesticidal compounds that are made by plants from genetic material that has been incorporated into the plant. For instance, researchers may insert the gene for the Bt pesticide protein into the genetic material of the plant. The pest-killing substance is then produced by the plant rather than the Bt bacterium. EPA regulates the protein and its genetic makeup but not the plant itself [28]. This is

also referred to as the non-conventional pest control product [22]. PIPs are biopesticides that are directly expressed in the tissue of genetically modified (GM) crops in order to defend them against pests such as viruses and insects. When eating on the transgenic crop tissue, insect pests ingest PIPs. Cry protein and double-stranded ribonucleic acid are examples of PIPs (dsRNA). There are various Cry protein types, each having a distinctive structure and toxicity that is exclusive to particular insect groups. Cry1 proteins poison Lepidoptera (such as the corn borer), whereas Cry3 proteins poison Coleoptera (such as the corn rootworm). The first-generation insecticidal PIPs were cry proteins. Recently, the next-generation dsRNA PIPs received approval. The first dsRNA PIP authorized by the FDA interferes with the synthesis of the Snf7 protein, a crucial vacuolar sorting protein, in order to kill the maize rootworm (*Diabrotica virgifera virgifera*) [29].

## 4. Production and Consumption of Biopesticide in India

As of right now, in India, there are 410 production units of biopesticides, 130 of which are private and 280 that are owned by the government. A total of 26 Central Integrated Pest Management Centre units, 31 ICAR/SAU (Indian Council of Agricultural Research institutions/State Agricultural Universities) units, 22 Department of Biotechnology-funded units, and various state sector units, including biocontrol laboratories, are among the units held by the government [30]. Additionally, since 2010, the Ministry of Agriculture and Farmers Welfare has helped roughly 32 IPM centers and 35 commercial enterprises manufacture biopesticides [31]. The state departments of agriculture and horticulture in Gujarat, Uttar Pradesh, Karnataka, Tamil Nadu, Andhra Pradesh, and Kerala have created several advanced biocontrol facilities to speed up the development of a small number of screened prospective biocontrol agents. Microbial pesticide manufacturing is also being carried out by Indian Council of Agricultural Research (ICAR) institutions and a few state agricultural universities (SAUs) [32]. Only a limited fraction of biopesticide manufacturing facilities, including those for botanicals, microorganisms, biocontrol insects, and pheromone lures and traps, have lately migrated to northern India as most were mainly occupied in southern India [30].

Major government organizations engaged in the commercial manufacturing of various biopesticides include central and state agricultural institutions, as well as a number of ICAR institutes. The Central Research Institute for Dryland Agriculture, Hyderabad, Directorate of Oilseed Research (ICAR), Hyderabad, Kerala Agricultural University (KAU), Kerala, Tamil Nadu Agricultural University (TNAU), Coimbatore, Central Plantation Crops Research Institute (CPCRI), Indian Institute of Horticultural Research, Bangalore, Central Research Institute for Dryland Agriculture, Hyderabad, and Kerala Agricultural University (KAU), Kerala are known for having specialized biopesticide production units. Universities that produce biopesticides against invading pests in the northeast include Assam Agriculture University and Central Agricultural University, Manipur. The manufacturing of biopesticides is carried out in the north by the Indian Agricultural Research Institute (IARI), New Delhi, the Punjab Agricultural University (PAU), Punjab, and the G.B. Pant University of Agriculture & Technology (GBPUA & T), Uttarakhand. The Indian Institute of Sugarcane Research (IISR), the Central Institute for Subtropical Horticulture, and Lucknow's Directorate of Plant Protection Quarantine & Storage—all of which are part of the Central Integrated Pest Management Centre—are the principal government organizations engaged in the production of biopesticides. In addition to these, a number of Krishi Vigyan Kendras (KVK) and state biocontrol labs have been established with government assistance, manufacturing biopesticides to meet local demand. NAFED, the National Agricultural Cooperative Marketing Federation of India, has also begun to advocate for the use of biopesticides [8].

Nearly 70% of the biopesticides are produced, according to estimates, by the public sector. Several significant companies include Biotech International Ltd. (New Delhi, India), International Panaacea Ltd. (New Delhi, India), Ajay Biotech Ltd. (Pune, MH, India), Deep Farm Inputs (P) Ltd., Pune Indore Biotech Inputs & Research Pvt. Ltd., Ganesh Biocontrol

System, Rajkot, GJ, India, Bharat Biocon Pvt. Ltd. (Chhattisgarh, India), Microplex Biotech & Agrochem Pvt. (Mumbai, MH, India), Excel Crop Care Ltd. (Mumbai, MH, India), Govinda Agro Tech Ltd. (Nagpur, MH, India), Kan Biosys Pvt. Ltd.,Chaitra Agri Organics, Mysore, KA, India, Jai Biotech Industries (Satpur, Nasik, MH, India), Gujarat Chemicals and Fertilizers Trading Company, Baroda, GJ, India, Gujarat Eco Microbial Technologies Pvt. Ltd., Vadodara, Indore, MP, India, Romvijay Biotech Pvt. Ltd., Harit Bio Control Lab., Pondichery Neyattinkara, KL, India, Devi Biotech (P) Ltd., Madurai, TN, Yavatmal, MH, India, T. Stanes & Company Ltd., Coimbatore, TN, India and Hindustan Bioenergy Ltd., Lucknow, UP, India. While few foreign businesses have entered the biopesticides industry, the majority of them collaborate with Indian businesses [8].

In India, the consumption of biopesticides makes up approximately 9% of total pesticide consumption [33] and, by 2050, is anticipated to represent up to 50% of the entire pesticide market [11]. The expected yearly growth rate is 2.5 percent [33]. However, as of now, the biopesticide market has still not developed as anticipated, and it is still relatively small in comparison to the market for synthetic pesticides [11]. The production is comparatively lower as a result of certain challenges at the industrial and policy levels. Nonetheless, the use of biopesticides for sustainable farming has been supported by the National Farmer Policy of 2007 [34]. Moreover, records show that India has increased its use of biopesticides over the past few decades. Neem, one of the most frequently used biopesticides in India, saw its consumption rise from 83 metric tons (MT) in 1994–1995 to 686 MT in 1999–2000, while *Bacillus thuringiensis* (Bt) use went from 40 to 71 MT over the same time period. The biopesticide use increased dramatically, above expectations, from 123 metric tons (MT) in 1994–1995 to 8110 MT in 2011–2012 [35]. The entire usage of biopesticides in India increased by 40% between 2014–2015 and 2018–2019 based on PPQS statistics [36], and, over time, reached 8847 and 8645 metric tons in 2019–2020 and 2020–2021, respectively [33], summarized in Figure 3. Meanwhile during the same time period, the consumption of chemical pesticides significantly decreased from 56,114 MT to 43,584 MT [37].

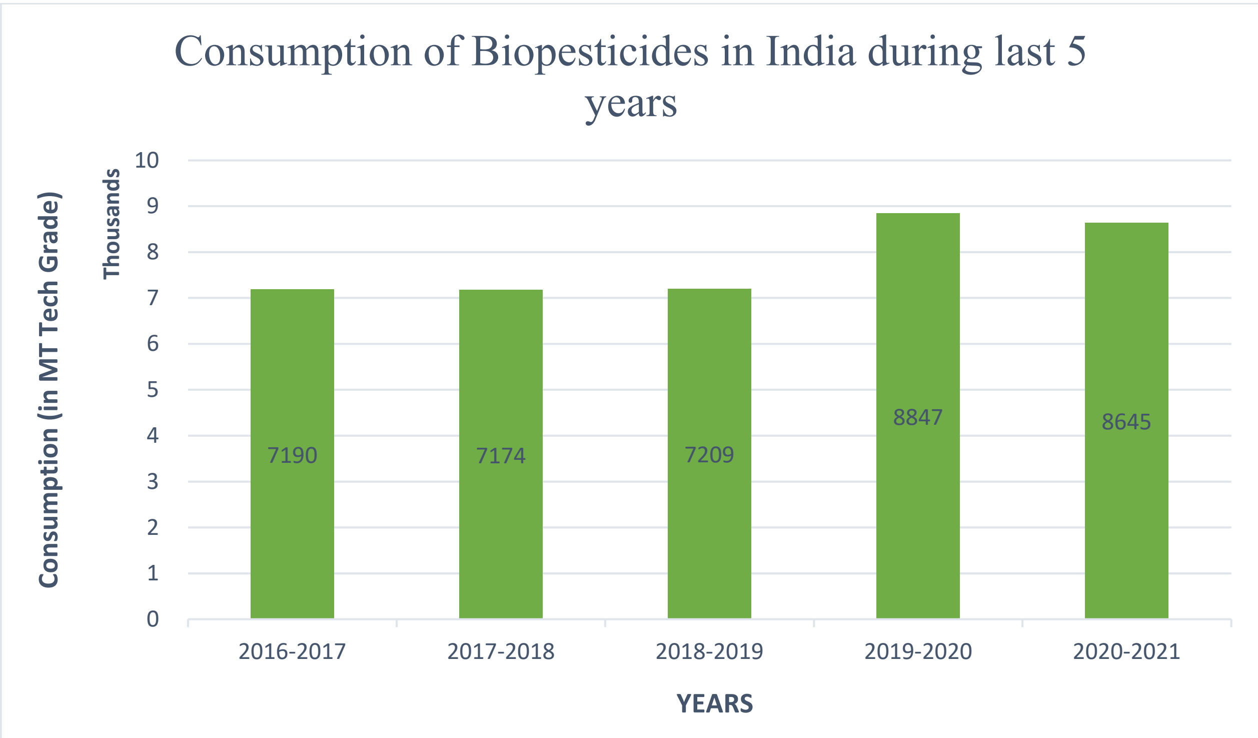


**Figure 3.** As of 22 July 2022, consumption of biopesticide throughout the previous five years in India.

The Insecticides Act of 1968 registers and regulates biopesticides. According to the Insecticide Act of 1968, only 12 different types of biopesticides have been registered in India [33]. They are:

1. *Bacillus thuringiensis var. israelensis;*
2. *Bacillus thuringiensis var. kurstaki;*
3. *Bacillus thuringiensis var. galleriae;*
4. *Bacillus sphaericus;*
5. *Trichoderma viride;*
6. *Trichoderma harzianum;*
7. *Pseudomonas fluorescens;*
8. NPV of *Helicoverpa armigera;*
9. *Beauveria bassiana;*
10. NPV of *Spodoptera litura;*
11. Neem-based pesticides;
12. Cymbopogon.

Except for a few biopesticides that are utilized in agriculture, the majority of biopesticides are used in public health [1].

## 5. Biopesticide Usage Pattern in India

In India, the Central Insecticides Board and Registration Committee (CIBRC), the primary regulatory body for all types of biopesticide usage currently has 970 biopesticide products registered with it [1]. Bacterial, fungal, viral, and other (plant-based, pheromone-based) biopesticides produce 29, 66, 4, and 1%, respectively, of the total amount of biopesticides [8] (Figure 4).

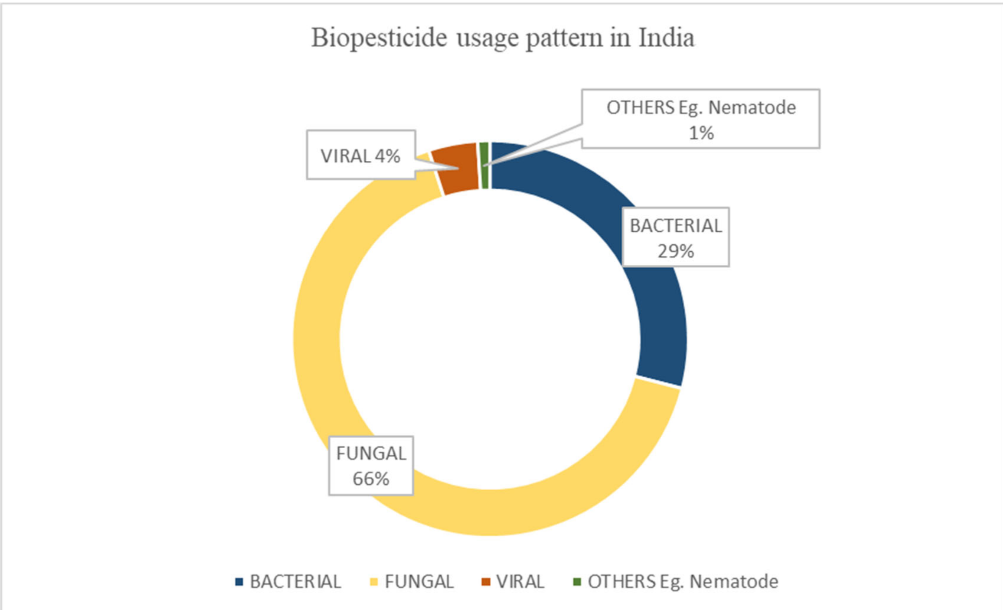


**Figure 4.** Pattern of overall biopesticide usage in India (2020).

Fungal products have the biggest percentage share of all biopesticides in India. Additionally, strains of *Trichoderma* are mostly used in the area of fungal biopesticides, and there are currently 355 products available on the Indian market for usage in the field. Even though there are many *Trichoderma*-based biopesticides on the market, only two species have been linked to recorded biocontrol activity [8]. Bt makes up around 15% of all bacterial biopesticides used, and is increasing at a rate of approximately 10% per year [18]. Viral biopesticides based only on nucleopolyhedrosis viruses (NPVs) are used in India to biocontrol *Helicoverpa armigera*, and their percentage usage is relatively low [8].

The microbiological sector dominated the Indian biopesticides industry in 2021 and is anticipated to continue to do so during the projected period, per a study of the biopesticides market. A *compound annual growth rate* (CAGR) of 13.8% is predicted for the microbial market. Since broad use of various microbial biopesticides has improved crop quality and protected against external attack by bacteria, fungi, and other pollutants, microbial biopesticides have seen a significant surge in popularity in recent years [38]. According to Table 1, the all-India figures moreover show a significant increase in the use of bio-pesticides in the areas under cultivation from the year of 2019.

**Table 1.** All-India statistics of area under cultivation and area under the use of bio-pesticide during 2017–2021 [39].

| YEAR | AREA UNDER CULTIVATION Unit: '000' Hectare | AREA UNDER USE OF BIOPESTICIDES Unit: '000' Hectare |
|---|---|---|
| 2017–2018 | 132,011 | 7738 |
| 2018–2019 | 141,555 | 7119 |
| 2019–2020 | 198,552 | 14,636 |
| 2020–2021 | 188,595 | 14,014 |

Statistics show that Maharashtra has utilized the maximum amount of biopesticides whereas Goa has utilized the minimum. The overall consumption of biopesticides has sharply increased in Rajasthan and Andhra Pradesh and steeply decreased in Orissa. Maharashtra, West Bengal, and Karnataka have consumed the most biopesticides, at 5549, 4416, and 3478 MT each, whereas Himachal Pradesh and Goa have used the least, at 36 and 38 MT each (Figure 5) (https://ppqs.gov.in/statistical-database, accessed on 22 November 2022). These data also explain why biocontrol initiatives in northern states of the nation have a lower impact than those in southern areas [8].

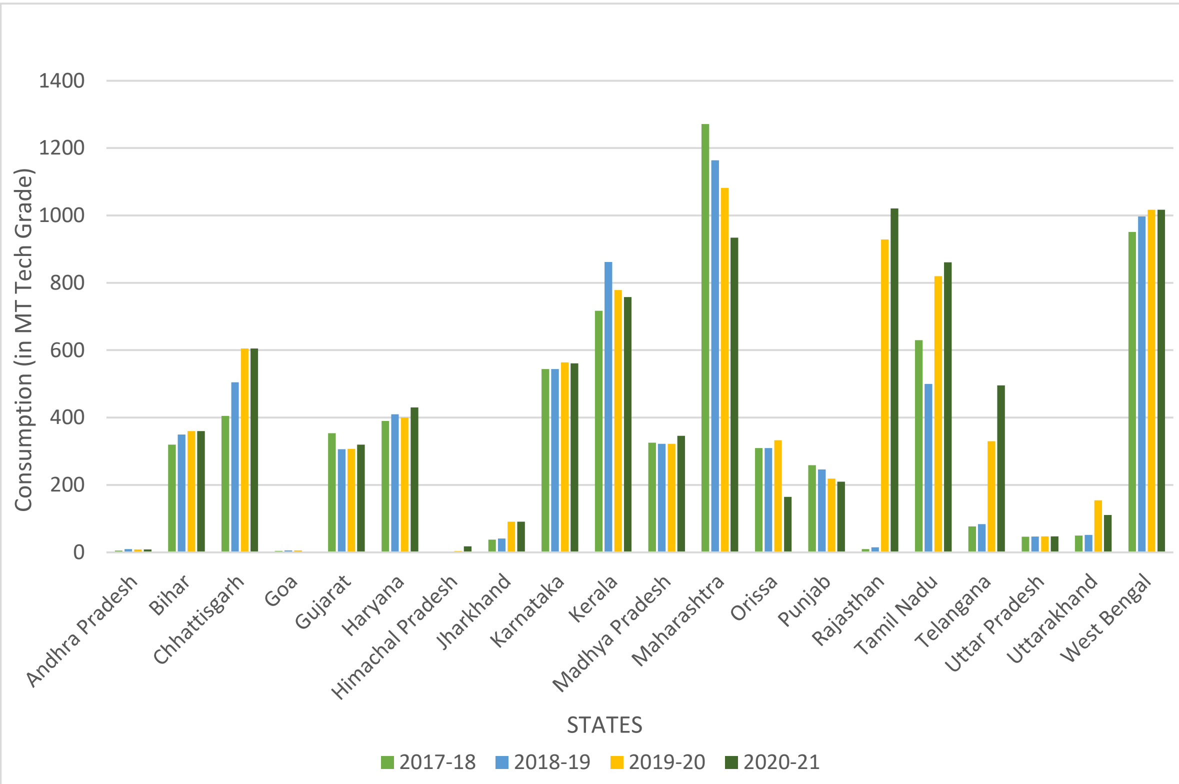


**Figure 5.** Consumption of states-wise biopesticide formulations from 2017–2021 [39].

## 6. Regulation of Biopesticide

Various regulations are being developed globally to register, monitor, and control the quality of these biopesticides [16]. To manage the regulatory activities, countries promoting them establish a variety of regulatory bodies, including committees, boards, and special organizations. These regulatory authorities create the dossier specifications for biopesticides and periodically update the dossier in light of regional and global demands [40].

In the United States, the biopesticides are largely regulated by three federal agencies. The Food and Drug Administration (FDA), the Animal and Plant Health Inspection Service (USDAAPHIS), and the Environmental Protection Agency (EPA) are the organizations. The USDAAPHIS is in charge of ensuring that these biopesticides are available for field and laboratory tests. If the studies demonstrate no obvious harmful effects on the environment or human health, the EPA encourages their usage on such grounds. Additionally, it permits the sale of pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA Act) and assures safety against pesticide residue in food and feed under the FFDCA Act (Federal Food, Drug, and Cosmetic). Furthermore, these biopesticides are evaluated by the FDA to see if they pose a risk to food, feed, or animals [40].

In China, the Institute for the Control of Agrochemicals of the Ministry of Agriculture is in charge of registering and regulating biopesticides. They are broadly categorized into six categories: botanical, microbial, biochemical, biological, genetically modified organisms (GMOs), and agro-antibiotics based on Chinese data requirements for pesticide registration. For the use of biotechnology products such as plant-incorporated pesticides, Canada, Japan, Australia, New Zealand, and Argentina have also developed science-based regulatory review systems that employ a proportionate-risk assessment approach. These systems depend on a trade-off between risks and benefits when making regulatory decisions [40]. Furthermore, a number of African nations use a variety of guidelines to create systems for the registration and control of biopesticides in the management of pests and diseases. A regional inventory of the regulatory environments was conducted by six country representatives from the West African region's Kenya, Uganda, Ethiopia, Tanzania, Nigeria, and Ghana as part of the Commercial Products (COMPRO II) project, which is overseen by the International Institute of Tropical Agriculture (IITA) [41]. Whereas the registration of biopesticides in EU (European Union) nations appears to be more challenging than in the rest of the world because the dossier is provided along with toxicological and environmental testing, it also requires efficacy evaluation. The Directive 91/414/EEC (EU 1991), which was created for chemical pesticides initially, also governed microbes, botanicals, and pheromones in the EU. The particular regulations for microorganisms were introduced to the Directive 91/414 by the amendments 2001/36/EC (EC 2001) and 2005/25/EC (EC 2005), while a new plant protection law was added to the EU in 2009 [41].

The Central Insecticides Board and Registration Committee (CIBRC) in India is the agency responsible for enforcing the Insecticides Act of 1968 and the Insecticides Rules of 1971, which govern the use of biopesticides [42]. As the highest-ranking advisory organization, CIB maintains a robust network of prominent researchers from all relevant areas. The RC is responsible for issuing registrations and licenses to aspiring biopesticide producers. This entire process adheres to a prescribed method. The novel biopesticide formulation is thoroughly examined using a number of quality control techniques, and any possible risks to human health or the environment are adequately assessed [32].

To guarantee the safety of people and animals, this board provides technical advice to the federal and state governments on issues pertaining to the production, marketing, distribution, and use of all insecticides, including biopesticides. After carefully inspecting their formulations and confirming the efficacy, toxicity, and packaging data provided by the importer or manufacturer, the registration committee of the CIBRC issues licenses to public and private businesses for the large-scale production, distribution, and sale of biopesticides to stakeholders. The Insecticides Act's sections 9(3B) (provisional registration for a novel active ingredient used in India) and 9(3) (regular registration) allow manufacturers to register new products [42]. This system lowers commercial barriers to product development by enabling commercial producers of those microbial pesticides assessed as generally safe to receive provisional registration and carry on market development while the product is pending full registration. Less information is required for registration under 9(3)B than under 9(3). For example, 9(3) B requires efficacy data on specific crops from two places over two seasons, whereas 9(3) requires the same from three locations. In terms of the content, virulence of the organism as measured by LC50, moisture content, shelf life, and secondary non-pathogenic microbial load, the CIB's set quality requirements must be met. Protocols have been established for evaluating these quality attributes [43].

The other regulatory bodies in India are the Central Integrated Pest Management Centre (CIPMC), Faridabad, the National Centre for IPM (NCPM) under the Indian Agricultural Research Council, and the Directorate of Biological Control, and the marketing of biopesticides to farmers is the responsibility of the Ministry of Agriculture and Farmers Welfare and the Department of Biotechnology (DBT). In addition to the aforementioned regulatory agencies, the Department of Biotechnology (DBT) funds research towards the creation of biopesticides. The National Agricultural Research System (NARS) and the National Accreditation Board (NBA) similarly carry out biopesticide quality control tests and instruct state agricultural departments in quality control procedures. In this regulatory chain, the latter is crucial in ensuring that biopesticides are distributed to farmers at a sustainable rate [43].

However, the legislative frameworks that were initially created for chemical pesticides and insecticides still play a significant role in the regulation of biopesticides and biocontrol agents. The intent of the legislation is the fundamental of the problem. The Act and the Rules' guiding principles treat biologicals such as chemicals because they were created to handle chemical pesticides [44]. Therefore, the evaluation of risks of biopesticides ought to be based on relevant scientific data rather than regulations that apply to synthetic compounds. As a consequence, it is necessary to alter the standards so that they reflect the nature of the various categories pertaining to the biopesticide active ingredients [14].

On the other hand, the major impediment to the commercialization of biopesticides is their regulatory approval [45]. The research and commercialization of pest control solutions involves a number of stakeholders, including scientists, regulators, marketers, and end users. Although some members of this chain are frequently involved from the very beginning of the development process, there are still many problems to be solved: marketers frequently disagree with the regulators and scientists, leaving end users perplexed by perceived flaws in the finished product [20]. The fact that these items typically contain live organisms or products generated from them, there are issues with the regulatory processes as well as barriers to importing and exporting them. Additionally, it has been noted that registration fees are often exceedingly expensive [41]. The commercialization of biopesticides thus clearly depends on regulation, which is frequently viewed as a development barrier. Despite the fact that regulations differ from nation to nation, the key concerns are that (i) regulations do not distinguish between living organisms and synthetic molecules, (ii) expensive testing is necessary irrespective of the size of the potential market, making niche biopesticide markets unprofitable, and (iii) the registration process can be extremely drawn out [46].

Thus, the governments can set policies at the international level by holding conferences, workshops, and meetings to raise the status of biopesticides and bioformulations. Governments should establish regulatory standards that would be globally accepted. Currently, problems with registration, use, import, and export occur since different countries have distinct rules and regulations. Therefore, there is a need for a common policy surrounding the use of biopesticides, and the regulation can draw up uniform actions or regulations that might be approved globally [47–49].

## 7. Role of Biocontrol agent in Biopesticide Development

The classical microbial control approach includes the use of various entomopathogens, where exotic microorganisms are imported and released for managing invasive pests for long-term control [50]. Various bacterial species and subspecies, such as *Bacillus*, *Pseudomonas*, etc., have been recognized as microbial pesticides (Table 2). The function of *Bt* δ-endotoxin has been well characterized [51] and has been shown to be safe with vertebrates and also for the environment [52]. Nowadays, the insecticidal properties of *Bt* toxin and bacteriocin are taken together for pest control. Bacteriocin is produced by plant growth-promoting rhizobacteria [53]. When the seed of cluster bean (*Cyamopsis tetragonoloba*) is associated with *Pseudomonas maltophilia*, root rot could be controlled by up to 40.8% when co-inoculated with *Rhizoctonia solani, R.bataticola, Sclerotinia sclerotiorum, and Fusarium oxysporum* under greenhouse conditions [54]. Another bacteria, *P. maltophilia*, along with a biocontrol agent, served as plant growth-promoting rhizobacteria in chickpeas when tested in combination with bioinoculants or alone. Under yield conditions, it reduced the crop mortality, thereby increasing the seed yield [55,56]. Entomopathogenic fungi form another important class of promising microbial biopesticides. They may be facultative or obligate, commensals, or symbionts of insects. Some fungi, such as *Streptomycetes*, produce toxins that act against insects [57]. Viral products for codling moth, *Heliothis zea*, and beet armyworm nuclear polyhedrosis virus have been registered to control pest Lepidoptera, such as the cotton bollworm and cotton budworm [58,59]. Protozoa have not yet proved to be an up-and-coming agent for biopesticide development. *Nosema* and *Vairimorpha* are the two genera, which, so far, have been found to attack lepidopteran and orthopteran insects [60]. Vertical transmission has been observed in Nosema while both vertical transmission and horizontal transmission are observed in *N. pyrausta*.

**Table 2.** Various entomopathogenic microorganisms and their target pests.

| **Entomopathogenic Bacteria** | **Target** | **Mode of Action** | **Reference** |
|---|---|---|---|
| *Bacillus thuringiensis* sp. *Aizawai* | Lepidoptera | Production of Bt δ-endotoxin | [61] |
| *Bacillus thuringiensis* sp. *Kurstaki* | Lepidoptera | | [61] |
| *Bacillus thuringiensis japonensis strain Buibui* | Coleoptera | | [61] |
| *Bacillus thuringiensis tenebrionis* | Coleoptera | | [61] |
| *Bacillus thuringiensis israelensis* | Diptera | | [61] |
| **Entomopathogenic Fungi** | | | |
| *Beauveria bassiana* | One or more pest of Acarina, Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera, Orthoptera, Thysanoptera, and others. | Cause muscardine insect disease | [62] |
| *Metarhizium anisopliae* | | | [62] |
| *Paecilomyces lilacinus* | | Attack the host by inserting their conidia in integuments and joints | [62] |
| *Metarhizium brunneum* | | | [62] |
| *Hirsutella thompsonii* | | | [62] |
| *Isaria fumosorosea* | | | [62] |
| *Lecanicillium lecanii* | | | [62] |
| *Lecanicillium longisporum* | | | [62] |
| **Entomopathogenic Virus** | | | |

**Table 2.** *Cont.*

| Entomopathogenic Bacteria | Target | Mode of Action | Reference |
|---|---|---|---|
| Nucelopolyhedrovirus | | | |
| *Helicoverpa zea* NVP | Lepidoptera | Kill the host when ingested and also spread during mating and egg laying | [21] |
| *Spodoptera exigua* NVP | Lepidoptera | | [21] |
| Granulovirus (GV) | | | [21] |
| Cydia pomonella GV | Lepidoptera | | [21] |
| **Entomopathogenic Nematode** | | | |
| *Heterorhabditis bacteriophora* | Several orders of soil borne pest | Inside the host, the nematodes release symbiotic bacteria that kill the host through bacterial septicemia | [50] |
| *Steinernema carpocapsae* | | | [50] |
| *S. feltiae* | | | [50] |
| **Entomopathogenic Protozoa** | | | |
| Microsporan protozoans | | The larva feeds on the viable spores and the infection cycle is repeated for the next generation. | |
| *Nosema* sp. | Lepidoptera and Orthoptera | | [60] |
| *Vairimorpha* sp. | | | [60] |

*Essential Oils as Biopesticides*

Essential oils (EOs) and plant extracts include significant natural compounds that can naturally degrade and can therefore be used to effectively control pests and diseases [63]. These natural products are mostly made up of volatile organic compounds (VOCs), which are predominantly from the phenylpropanoid and terpenoid families and have a high vapor pressure at room temperature. There are numerous abiotic conditions that cause essential oils to degrade quickly (making their handling easy since there are no residue problems). They offer a broad spectrum of activity are simple to process and utilize as they are less persistent, making them safe for people and the environment [64]. The application of EOs in more environmentally sustainable agronomic techniques has been the subject of numerous research investigations. Given their antibacterial, antifungal, insecticidal, acaricidal, nematicidal, and herbicidal properties, EOs have a considerable biopesticidal potential according to a number of studies. Since EOs' biocidal effects can be specific, their application may be suited for integrated pest management (IPM) [65]. However, EOs and plant extracts are biologically unstable because environmental factors, including pH, oxygen, light, and mild temperatures, can quickly cause them to degrade. In general, EOs have significant volatility and poor water solubility. As a result, efforts are being undertaken to address these issues [63].

In a study, EOs of *Thymus zygis, Thymus vulgaris, and Mentha suaveolens* were found to be strong ixodicidal and antifeedant agents. It was suggested that these plants be developed as biopesticides to successfully manage ticks and insect pests. It was interesting to note that these EOs' interactions had synergistic effects as well. In a large-scale field trial, the use of aqueous extracts of *Murraya paniculata, Cassia tora, Amphineuron opulentum, Tithonia diversifolia*, and *C. alata* reduced the red spider mite population, a significant pest of tea, while having less of an effect on natural enemies and increasing the tea plant yield without having a fatal impact on the plants or the consumers. Nonetheless, the larvicidal activity of EOs from five different piper species, including *Piper aduncum, P. marginatum, P. gaudichaudianum, P. crassinervium, and P. arboreum*, against the Aedes aegypti mosquito that causes yellow fever, demonstrated up to a 90% lethality at a screening concentration of 100 pm, making these EOs potential alternatives for controlling *A. aegyp* [63].

## 8. Technological Advancement in Enhancing Biopesticide Efficacy

Until now, there are no established processes for preparing or assessing efficacy in field situations. With the advent of nano-technology and others, there are new and better possibilities for enhancing biopesticide efficacy.

### *8.1. Nanotechnology*

Nano-biopesticides contained in carriers are being designed, and help in the regulated release of active components to obtain desired effects in a particular environment. Adding nano-biopesticides to biopolymers has enhanced stiffness and penetrability. Crystallinity, thermal stability, biodegradability, and solubility are also enhanced [66]. However, these techniques need to be improved. The soil-based application of nanomaterials resulted in the growth of mutualistic microorganisms that promote the plants' activities [67]. Silver nanoparticles synthesized using *Trichoderma harzianum* have shown to inhibit the growth of *Fusarium oxysporum*, a causative agent of wilt disease in sweet pepper plants [68]. Sometimes, coatings of silver-based nanoparticles can induce toxicity, which can be reversed by biocompatible coatings, thereby enhancing seed germination in plants. Some nano-pesticide delivery techniques that are used with different functionalities for plant protection include nano-encapsulates, nanocontainers, nano-emulsions, and nano-cages [69]. Thus, nanotechnology can help in the development of less toxic biopesticides with suitable safety profiles and an enhanced stability of the active agents, increased activity on target pests, and adoption by the end-users, and seems promising in the direction of formulation [70–72].

### *8.2. New Strains*

Several new strains have recently been discovered containing substances that can be used as biopesticides (Table 3), but more testing is required to prove their efficacy [14].

**Table 3.** List of various substances with pest control properties.

| Product | Target Pest | Chemical Nature | Reference |
|---|---|---|---|
| Products of the fungus *Trichoderma harzianum* | *Fusarium* root rot | Fungicide | [73] |
| Strains of the fungus *Talaromyces flavus* SAY-Y-94-01 | Anthracnose caused by *Glomerella cingulata* and *Colletotrichum acutatum* | Fungicide | [74] |
| *Bacillus thuringiensis* var. *tenebrionis* strain Xd3 (Btt-Xd3) | Alder leaf beetle (*Agelastica alni*) | Insecticide | [75] |
| Extract of the species *Clitoria ternatea* (butterfly pea) | *Helicoverpa* spp. | Insecticide | [76] |
| Olive mill waste | Various pests | Fungicide and Bactericide | [77] |
| Alkaloid compound oxymatrine | *Spodoptera litura*, *Helicoverpa armigera, Aphis gossypii* | Insecticide | [78] |
| Stilbenes isolated from grapevine extracts | *Spodoptera littoralis* | Insecticide | [79] |
| Fermentation products of the bacterium *Lactobacillus casei* strain LPT-111 | Angular leaf spot caused by *Xanthomonas fragariae* | Bactericide | [80] |

### *8.3. Recombinant DNA Technology*

Novel fusion proteins are being adopted to develop next-generation biopesticides. The principle is to combine a toxin with a carrier protein that makes it toxic only to insect pests when consumed orally and not to the higher organism. Initially, it was toxic only when injected by a predator into a target prey [81]. The microbial system may be used to form the fusion protein as a recombinant protein. The latter can be scaled up for commercial formulations and industrial production. Several other advanced, innovative approaches are being designed to develop biopesticides as efficient, acceptable, and effective pest control measures.

### 8.4. RNAi for Biopesticide

The RNAi technology is a new intervention for combatting pests. Double-stranded RNA (dsRNA), the leading molecule of the RNAi system, has been shown to provide protection under in vitro conditions, without the need for integration as a transgene. So far, some success has been gained in terms of viruses and fungi, and it seems a promising alternative against chemical pesticides if the cost of generating dsDNA reduces. The functional foliar application of dsRNAs targeting the plant viruses Pepper mild mottle virus (PMMoV), Alfalfa mosaic virus (AMV), and Tobacco etch virus (TEV) was first reported by Tenllado and co-workers in 2001 [82]. Other alternatives used a crude extract of *E. coli* HT115 expressing the same dsRNA fragments used previously and achieved similar positive results with viral co-inoculation, though the window of resistance was limited to five to seven days [83]. Since the pioneering work of Tellendo, many other positive reports have been obtained against Sugarcane mosaic virus coat protein using the HT115 system developed earlier by Tenllado [84]. Bacterial extracts have been used to generate dsRNA against Cymbidium mosaic virus coat protein [85,86]. Direct application on detached barley leaves of a dsRNA targeting three CYP450 genes could inhibit *Fusarium graminearum* growth [87]. Wang and co-workers targeted two Dicer-like genes in *Botrytis cinerea* on fruit, vegetable, and flower surfaces and thereby showed that RNAi could play a role in the post-harvest protection of agricultural produce in addition to pre-harvest protection [88]. In the case of protection against arthropod pests, there are technical challenges involving the application of topical RNAi strategies. This is because there is a lack of amplification of the RNAi silencing signal and dsRNA degradation during ingestion [89]. However, mortality could be caused by the oral uptake of dsRNAs targeting critical genes in some arthropods. Though success could be gained for some species, more research is needed before this technology could be commercialized. The risk involving this approach is evident and includes the potential for toxic fermentation by-products, the presence of selective antibiotics used in growth media, and the uncertain GMO status of a non-purified product.

## 9. Usage of Biopesticide as a Contributor to Agriculture and Sustainable Development

Biopesticide-driven sustainable agriculture has social acceptance, increases economic productivity, and lessens environmental hazards. These features represent the ternate approach to sustainable development. There are several advantages involving the use of biopesticides. They can be inhibitory through multiple modes of action, such as metabolic poison, neuromuscular toxins, gut disruptors, non-specific multisite inhibitors, and growth regulators [90]. The chances of developing resistance are completely eliminated because of these multiple modes of action against targeted pests. This is why there is a declining number of classical pesticides and increased demand for biopesticides. The benefits include a reduced pest resistance, reciprocal use of synthetic pesticides, eco-friendliness, low-toxicity properties, specificity (does not impact non-target organisms and humans), biodegradability, the very minor problem of post-harvest contamination, stability against abiotic stress [91,92], and compatibility in integrated pest management (IPM). Like other natural resources, such as biofertilizers and biostimulators, biopesticide application in modern farming creates a balance amongst socio-cultural relevance, economic productivity, and environmental protection, and is considered pivotal to sustainable agriculture. Thus, we can say that the integration of public policy into the four sections (including technology) would be the basis of sustainable development [48,93].

## 10. Potential Risk of Biopesticides to Human and Ecosystem Health

Most biopesticides can be categorized as basic or low-risk substances with a minimum risk factor. Many of them are employed in concentrations that are similar to those found in nature. Low-risk compounds break down relatively quickly, leaving little to no trace in the environment or food that could harm living things [94], contrary to slow-degrading chemical pesticides in the ecosystem [49].

The likelihood of negative effects on human health caused by microbial pesticides is extremely low, and the observation that crystal protein must be converted into its active toxic form in an alkaline environment—a condition present in insect guts but absent in the majority of mammalian systems—may help to partially explain the lack of animal and human toxicity. In addition, the targeted insect species selectively express the crystal protein binding site, which is purportedly absent in mammalian systems [95]. The Bt-based biopesticides are typically regarded as a safer and more environmentally friendly substitute for chemical pesticides. Commercial Bt species are thought to be non-infectious, and opportunistic infections in humans have only rarely been linked to them [96]. *Bacillus thuringiensis* is widely distributed throughout the world, making human exposure to it ubiquitous. *B. thuringiensis* was found to be a likely contaminant in 95% of instances rather than the root of the clinical illness that led to the specimen collection. In conjunction with its use as a biopesticide in the US, *B. thuringiensis* has been discovered in human bodily fluid cultures. The organism has also been found in skin infections in burn patients. One evaluation conducted in a hospital revealed that the detected strains originated from contaminated water used to treat the burns. Insecticidal activity and other microbiological features required for *B. thuringiensis* to be employed as a biopesticide were later found to be absent from the isolates. Although the *B. thuringiensis* strains discovered in these infections were not due to their usage as biopesticides, the research did demonstrate that pathogenic impacts from this organism in immunocompromised hosts were plausible [95]. Furthermore, according to a study conducted on mice, frequent exposure to biopesticide aerosols may cause sub-chronic lung inflammation, which may aid in the emergence of serious lung disorders. Bt aerosols were inhaled without causing any observable airway irritation, indicating that exposure will not cause a warning symptom, rendering the exposure insidious [96].

In the context of biocontrol, an assessment of the effects of the biopesticide azadirachtin on the queens of the stingless bee *Partamona helleri* using the neonicotinoid imidacloprid as a toxic reference standard, during development, showed that azadirachtin caused deformations, slowed down development, and decreased the size of reproductive organs. Each of these elements has the potential to jeopardize colony viability. According to the study's findings, *P. helleri* queens were toxicologically at risk from azadirachtin [97]. Additionally, melanization and antifeedant activities demonstrated that neem extract may have an impact on the insect's hormonal level [98].

Over the past few years, abamectin-containing plant protection products have seen a substantial increase in terms of use. Studies showed that abamectin has a minimal toxicity for mammals, but it can cross the blood–brain barrier in fish and induce toxicity. Abamectin was tested for acute lethality on *Lithobates catesbeianus* and caused a reduced activity and loss of equilibrium posture. The loss of equilibrium posture could make them more vulnerable to predators and reduce the amount of food available to them in the wild, both of which could have a negative impact on their capacity to survive in the wild. In the current investigation, it was seen that animals with a loss of equilibrium posture consumed less food than test organisms that were not affected. These observations are consistent with abamectin's mode of action, which blocks the interneuronal stimulation of excitatory motoneurons and causes a flaccid paralysis by inhibiting GABA neurotransmission [99]. Another study found that the biopesticide Derisom, which is based on karanjin, significantly altered *Cyprinus carpio*'s biochemical parameters at low concentrations. Upon exposure to derisom, the total protein content and enzymes involved in protein metabolism, such as glutamate dehydrogenase, alanine amino transferase, and aspartate amino transferase, were altered in the gill, liver, kidney, and muscle. The degree of biochemical alterations brought on by exposure to biopesticides varied among the organs, but there were some similarities to an extent. The alterations in biochemical parameters were a crucial marker for tracking the condition and well-being of fish exposed to pesticides. Thus, as the data indicate, the application of biopesticides in agricultural areas requires monitoring [100].

Thus, the lack of a thorough examination into the harmful consequences of biopesticides and the fragmentary information on this subject are quite concerning. In addition to their direct toxicity, all of the major classes of biopesticides can have a wide range of subtle adverse consequences. Despite the fact that this field of study is expanding, the existing risk assessment methodology is insufficient to accurately evaluate all of the potential negative effects that these bioagents of control may have [101]. When integrating biopesticides into IPM and organic programs, it is crucial to have a better understanding of the potential risks involved with their use against natural enemies. The adverse effects can differ significantly depending on a number of variables, including the endpoint (lethal vs. sublethal and instar evaluated), pesticide persistence, and the development plans of the non-target species in issue [102]. As a result, in the present situation, safety testing and risk assessment need to become more accepted practises in order to ensure the safety of exposed workers, the environment, and the management of potentially harmful side effects [103,104].

## 11. Biopesticide Application and Its Limitations

Biopesticides have proved to be a very positive alternative to chemical pesticides; however, there is a long way to go before they can completely replace the other synthetic market. There are several pieces of evidence for the success of pesticides against a wide range of crop plants. However, it is not devoid of limitations.

- Availability of plant sources: the production of a biopesticide is dependent on the availability of host plants in large quantities and their cultivation. Until now, these plants are grown for food, medicine, etc. Moreover, engaging in commercial production will require huge land areas, which are mostly all reserved for crop cultivation, hence the incapability of meeting the correct applied dosage remains inappropriate.
- Formulation: this is challenging as more than one active compound with different chemical properties can be derived from one plant. The extraction procedure requires the use of organic solvents, which pollutes the environment through their disposal.
- Shelf life: compared to their rate of biodegradability, they have a very short shelf life. This has an impact on the cost of development, production methods, and inconsistency in their field performance.
- Specificity: microbes form a very small portion of the entire pest community. Hence, these microbial biopesticides are only effective in controlling a small portion of the pest population. They are also slow in action compared to chemical pesticides.
- Efficacy: the effectiveness of microbial pesticides is susceptible to adverse climatic conditions. The effect is reduced by heat, desiccation, UV light, etc. Hence, it is important to precisely design the system of delivery. Moreover, they show mild toxicity to the pathogens and are inferior to the efficacy of conventional pesticides.

Overall, the cost of manufacturing a biopesticide is very high. In this regard, both private and public sectors should cooperate, develop, manufacture, and sell this eco-friendly product. The constant discovery of active compounds and scientific work on their formulation and delivery would enhance biopesticides' commercialization and usage. The Indian Government has already taken the initiative to subsidize the availability of biological pesticides to farmers in order to promote the commercialization of biopesticides. Still, the regulation of processes that enhance the registration of low-risk substances can boost the exploitation and accessibility of biopesticides in the market.

## 12. Conclusions

For more than 50 years, biopesticides have been proven to be a convenient, efficient, and budget-friendly alternative for the management of insect pests and weeds in the field of agriculture and public health in India. They have shown a significant contribution to the enhancement of the agricultural production and global income of the farmers. Presently, India is independent in producing biopesticides and also in their export services. The most frequently used species in the Indian biopesticide industry is *Trichoderma viride*. This biopesticide has already been utilized in 87 various crops, 70 soil-borne diseases, and 18 foliar diseases.

Biopesticides can be beneficial for farmers in decreasing the use of chemical pesticides because of their sustainable and environment-friendly qualities, as well as potentially posing less of a threat to mankind. Thus, it is advised that public and commercial sectors must work together to encourage the farmers from the basic level by providing an integrated policy and guidelines for the use of biopesticides. In that regard, discovering new substances and researching their formulation and delivery would foster the commercial aspects of biopesticides. It is necessary to induce more research work on integrating biological agents into common production methods of biopesticides. In addition to that, the promotion of low-risk compounds with incentives could also intensify the commercialization of biopesticides at the market level. However, more field research is needed to examine the efficiency of specific pest problems in different cropping systems.

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