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Recent Advances in Biopesticides: A Review of Efficacy and Environmental Impact

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Abstract

Biopesticides are a vital component of sustainable agriculture, offering a safer alternative to synthetic pesticides. This review provides an overview of recent advances in biopesticides, including their types, efficacy, and environmental impact. Microbial, plant-based, and biochemical biopesticides have shown promising results in controlling pests and diseases. While efficacy is comparable to synthetic pesticides, biopesticides have a more favorable environmental profile, with reduced toxicity to non-target organisms and biodegradability. However, challenges persist in registration, regulation, and public acceptance. Future directions include genetic engineering, nanotechnology, and integrated pest management strategies. This review highlights the potential of biopesticides in reducing the environmental footprint of agriculture and ensuring food security.

Keywords: Biopesticides, Sustainable agriculture, Efficacy, Environmental impact, Microbial biopesticides, Plant-based biopesticides

Introduction

Biopesticides are naturally occurring compounds or agents that are obtained from animals, plants, and microorganisms such as bacteria, cyanobacteria, and microalgae and are used to control agricultural pests and pathogens. Biopesticides are derived from natural materials, including plants, animals, bacteria, and certain minerals, according to the US Environmental Protection Agency (EPA, 2021). Products from these biocontrol agents, such as genes or metabolites, can be used to prevent crop damage. Compared to traditional chemical pesticides, biopesticides are much more advantageous to use because they are host-specific and environmentally friendly (Essiedu *et al.,* 2020). Because biopesticides are host-specific and environmentally friendly, they are significantly more favorable to utilize than their conventional chemical counterparts (Essiedu *et al.,* 2020). Biopesticides can significantly enhance the use and application of agro-based chemicals in the agricultural sector to protect crop plants against invasive and infectious pests (Essiedu *et al.,* 2020 and Chang *et al.,* 2003). According to Gasic and Tanovic (2013), biopesticides are byproducts and products of naturally occurring creatures like plants, nematodes, insects, and microbes. Biopesticides can be classified into a number of categories, including botanicals, antagonists, compost teas, growth promoters, predators, and pheromones, depending on the kind and source of their active ingredients (Semeniuc *et al* 2017). Because they contain significant levels of bioactive chemicals and antimicrobial agents, plants and microbes are the main sources of biopesticides (Nefzi *et al.,* 2016).Plants contain phenols, quinones, alkaloids, steroids, terpenes, alcohols, and saponins among their active constituents (Mizubuti *et al.,* 2007).

Importance of biopesticides in sustainable agriculture

Biopesticides are as effective as synthetic pesticides in management of crop pests (Birech *et al*., 2006). Natural products are also eco-friendly since they are easily biodegradable and therefore do not pollute the environment (Leng *et al.,* 2011). Consumer tastes and preferences fluctuate over time and following the demand for organically produced food, this makes biopesticides suitable alternatives to synthetic pesticides (Okunlola, and Akinrinnola 2014). Biopesticides have very short pre-harvest intervals and are therefore safe to use on fresh fruits and vegetables (Khater., 2012). Additionally, because they are target specific, they have little effect on advantageous organisms like natural enemies (Shiberu, and Getu, 2016). Because they work well in modest doses, their application encourages sustainable pest management, which advances sustainable agriculture (Nawaz *et al.,* 2016). Natural pesticides do not lead to the development of insect resistance (Islam *et al.,* 2014). Since their source materials are readily available and may be found in the natural world, where some of them are also used for other purposes like food and feed, they are affordable to obtain (Srijita, 2015). Due of their lack of toxicity, biopesticides are safe goods for both consumers and applicants (Damalas and Koutroubas 2015). Therefore, biopesticides can suitably be incorporated in integrated pest management (IPM) which helps reduce the amounts of chemical pesticides used in management of crop pests (Sesan *et al.*, 2015). Natural products decompose quickly which makes them safer for use in the environment (Kawalekar, 2013). Natural source pesticides have extremely short re-entry intervals that ensure the applicant's safety (Stoneman, 2010). Biopesticides are also employed in agricultural soil cleansing by introducing significant microbial species (Javaid et al 2016).

Overview of the review

Chemical pesticides have been quite effective over the years in controlling illnesses and pests. On the other hand, their extensive and prolonged use led to biomagnification and insecticide resistance, which in turn led to export limitations. A number of issues emerged that put human health and the environment at risk, including contaminated soil and water and a sharp rise in hazardous residues found in many primary and derived agricultural products. An estimated $8.1 billion is spent annually on mitigating the harm to the environment and social economy (Shen and Zhang, 2000).Researchers have studied the ability of certain plants to defend themselves against pests by utilizing compounds that the plants produce (Rizvi *et al.,* 2016). Some plants have been found to contain compounds that are effective against several pests including fungi and nematodes (Hussain *et al.*, 2015 and Sidhu *et al.,* 2017). Some species of microorganisms have antagonistic properties towards other species and are therefore effective as biopesticides (Aw and Hue 2017).(Ngegba *et al.,* 2018) reported that extracts of neem (Azadirachta indica) and Mexican sunflower (Tithonia diversifolia) inhibited growth of rotting disease pathogens of tomato, up to 100% for Aspergillus niger, Fusarium oxysporum, and Geotrichum candidium. In a dosage-dependent poisoned food technique experiment, extracts from castor seeds (Ricinus communis) effectively inhibited the growth of post-harvest pathogens, Penicillium oxalicum and Aspergillus niger of yams (Dioscorea alata) (Patrice et al., 2017). According to Devi et al. (2017), applying extracts from Duranta erecta and Lasonia ineruis had comparable effects on post-harvest fungi such as Fusarium solani, Rhizopus arrhizus, and Sclerotium rolfsii. Fungi that cause up to 50% of chick pea (Cicer arietinum) wilt were inhibited by methanolic extracts of Chenopodium ambrosioides against Fusarium oxysporum f.sp. ciceris (Minz et al., 2012).

A biopesticide formulation containing onion (Allium cepa) and ginger (Zingiber officinale) was evaluated for efficacy against tomato fruit worm (Helicoverpa armigera) and registered a 70% - 80% control (Sumitra *et al*., 2014). During the study, yield increment was also observed on plants treated with the formulation compared to the untreated controls. (Muzemu *et al.,* 2011) reported over 50% reduction of rape aphids (Brevicoryne brassicae) and tomato red spider mites (Tetranychus evansi) by powder extracts of Lippia javanica and Solanum delaguense. Populations of Megalurothrips sjostedti were reduced by extracts of Piper nigrum, Cinnamomum zeylanium and Cinnamomum cassia and were reported to be strong repellents (Abtew et al., 2015). Number of larvae and pupa of Helicoverpa armigera were effectively reduced by extracts of Curcuma longa, Allium sativum and henge (Ferula assa-foetida) in a study by (Shah *et al.,* 2013). Extracts of Artemisia herbaalba, Eucalyptus camaldulensis and Rosmarinus officinalis soaked on leaves of broad bean (Vicia faba) caused a mortality of 60% - 100% of green peach aphid (Myzus persicae) after 24 hours of exposure in dose dependent in vitro experiments (Nia *et al.,* 2015). In another study, topical application of Azadirachta indica, Mangifera indica, Polyalthia longifolia, Annona squamosa and Ficus benghalensis caused a 100% mortality of bed bugs (Cimex lectularius) after 19 seconds of contact (Parte *et al.,* 2015). The effectiveness of plant extracts on insects is credited to the solvents used and their ability to extract major compounds with insecticidal properties (Oyedokun *et al.,* 2011 and Barbosa *et al.,* 2013).

According to Barbara Bosa et al. (2013), Bacillus subtilis, Pseudomonas putida, and Pseudomonas aeruginosa were assessed against Fusarium oxysporum f.sp. ciceris and were found to have superior control over seed treatment, leading to an increase in growth parameters.Compounds produced by Bacillus species have been shown to be effective against Xanthomonas oryzae pv. oryzae and Rhizoctonia solani, two significant fungal infections (Beric *et al.,* 2012 and Islam *et al.,* 2012). Chaetomium globosum compounds have also been shown to be effective against significant rice fungal diseases, including Magnaporthe grisea and Puccinia recondita (Park *et al.,* 2005). Streptomyces griseus was used, and Anitha and Rabeeth (Anitha et al., 2009) observed that the severity of tomato fusarium wilt was reduced. Bacillus subtilis, Pseudomonas aeruginosa, and

Stenotrophomnas maltophilia showed antagonistic behavior against Erwinina carotovora in a seeded medium experiment (Selim *et al.,* 2016).

Types of Biopesticides

Microbial Biopesticides

Fungicides and bactericides these biopesticides generally inhibit or disrupt the process of translation and thus protein synthesis in numerous ways, including through binding of 50S ribosomes in prokaryotes, to prevent the transfer of peptides and inhibit chain elongation (such as blasticidin) (Parker *et al.,* 2019 and Svidritskiy *et al.,* 2013). Sometimes they interfere with the binding of aminoacyl tRNA to 30S and 70S ribosomal subunit complexes and inhibit translation (such as kasugamycin) (Schuwirth *et al.,* 2006). In the case of streptomycin and mildiomycin, binding with the 30S ribosomal subunit causes abnormal synthesis of protein (nonfunctional) and blocks the activity of peptidyltransferase, respectively (Arena 1995 *et al.,* and Feduchi *et al.,* 1985).They can also disrupt plasma membrane permeability and cause leakage of substances (amino acids and electrolytes), thereby causing cell death (such as natamycin), and can inhibit chitin synthase activity (polyoxins) and inhibit trehalase, preventing the formation of glucose (validamycin) (Gwinn, 2018).

Biochemical Pesticides

The source of these insecticides is vegetation. Throughout their evolutionary history, plants have produced a wide range of chemicals that can aid in the defense against pathogenic microbes during infection and attack. Steroids, alkaloids, phenolics, terpenoids, phenylpropanoids, and nitrogenated chemicals are some of these substances. For example, the first insecticide used to kill plum beetles in the 17th century was nicotine, which was derived from tobacco leaves (Schorderet *et al.*, 2019 and Duan *et al.,* 2016). Since most herbivorous insects are sensitive to nicotine, pesticides made from tobacco have been dubbed "green pesticides" because of their high activity and low toxicity (Duan *et al.,* 2016).It has been mentioned that tobacco contains some beneficial ingredients, like nicotine and solanesol, which have strong antibacterial properties against *Micrococcus lysodeikticus, Bacillus subtilis,* and *Staphylococcus aureus*. Certain insecticides, like nicotine and azadirachtin, work by binding to sodium channels, inhibiting insect growth regulators, or interfering with respiratory enzymes (Elgar, 2018). In contrast, microbicides interfere with metabolic processes, damage the integrity of the plasma membrane, and prevent the formation of conidia (Gomiero, 2017).

Plant-Based Extracts and Essential Oils

Over the last several years, plant-based extracts and essential oils have emerged as attractive alternatives to synthetic insecticides for insect pest management. These insecticides are naturally occurring insecticides as they are derived from plants and contain a range of bioactive chemicals (Magierowicz *et al.,* 2020) Depending on physiological characteristics of insect species as well as the type of plant, plant extracts and essential oils (EOs) exhibit a wide range of action against insects: they can act as repellents, attractants, or antifeedants; they also may inhibit respiration, hamper the identification of host plants by insects, inhibit oviposition and decrease adult emergence by ovicidal and larvicidal effects (Ali *et al.*, 2017). Their composition varies greatly. Well-known examples in this regard are neem and lemongrass oil, which are very common in global herbal markets. A comprehensive study by (Halder *et al.,* 2013) showed that a combination of neem oil with entomopathogenic microorganisms, including *Beauveria bassiana*, was very successful against vegetable sucking pests. However, it is very important to determine the dose of azadirachtin content in neem oil so as not to kill the nontarget organisms (Mordue et al., 2005). A similar strategy has to be established for the entomopathogenic fungi that need to be supported by complementary laboratory bioassays, station, and/or field experiments for effective management of the target pests without affecting nontarget insects (Dannon *et al.,* 2020). As regards the marketability of essential oils, they in fact, represent a market estimated at USD 700.00 million and a total world production of 45,000 tons, and industries in the US are able to bring essential oil-based pesticides to market in a shortened time period, as compared to the time taken in conventional pesticide launch (Parween and Jan 2019).

Challenges and Future Directions of Biopesticides

Biopesticides provide advantages as safe environment and healthy food for human consumption, there are factors that limit their full adoption as pest and disease management options. High doses of the constituent compounds are needed for efficacy under field conditions (Shiberu and Getu 2016). During formulation, it is sometimes challenging to get the right proportions of the active and inert ingredients needed. There are also no standard preparation methods and guidelines for efficacy testing especially under field conditions (Okunlola, and Akinrinnola 2014). While the in vitro tests produce excellent results, there are always inconsistencies at the field due to low shelf life and sometimes poor quality of source materials or preparation methods.SAdoption of biopesticides of predatory nature need a lot of consideration such as host crops and dispersal capability (Gerson, 2014). Crop coverage and exposure time are essential and for a small acreage this could prove expensive since application may be manual (Lanzoni *et al* 2017). Registration of the products requires data on chemistry, toxicity, packaging and formulation which is not always readily available (Gupta and Dikshit 2010). The cost of producing a new pesticide product is usually high and has a lot of resource limitations (Stoneman, 2010). Lack of a readily available market makes it hard to invest in biopesticides (Stoneman, 2010). There are insufficient facilities and capital for production of biopesticides especially in the slowly developing countries. The shelf life of natural products is dependent on many factors such as temeperatures and moisture which are sometimes difficult to control (Koul, 2011). Biopesticides also face high competition from synthetic pesticides and if the former were produced for a small agricultural activity, the costs may be relatively high and therefore not feasible. There is insufficient awareness about biopesticides especially among the small-scale growers, stake holders and policy makers. In the case of microbial pesticides, there is usually no trust in the value and use chain between producers, buyers and users and considering the risk of importation, synthetic pesticides appear reliable (Kumar and Singh 2015).

Efficacy of Biopestcides

Biopesticides act in a variety of ways on microorganisms depending on their type and nature. A few mechanisms through which biopesticides attack or kill pathogens are listed as follows (Liu et al., 2021). Fungicides and bactericides are biopesticides generally inhibit or disrupt the process of translation and thus protein synthesis in numerous ways, including through binding of 50S ribosomes in prokaryotes, to prevent the transfer of peptides and inhibit chain elongation (such as blasticidin) (Gwinn, 2018 and Parker et al., 2019). Sometimes they interfere with the binding of aminoacyl tRNA to 30S and 70S ribosomal subunit complexes and inhibit translation (such as kasugamycin) (Schuwirth et al 2006). In the case of streptomycin and mildiomycin, binding with the 30S ribosomal subunit causes abnormal synthesis of protein (nonfunctional) and blocks the activity of peptidyltransferase, respectively (Arena et al., 1995, Feduchi et al., 1985). They can also disrupt plasma membrane permeability and cause leakage of substances (amino acids and electrolytes), thereby causing cell death (such as natamycin), and can inhibit chitin synthase activity (polyoxins) and inhibit trehalase, preventing the formation of glucose (validamycin) (Gwinn., 2018).

Insecticides upon reaching nerve endings, release gamma-aminobutyric acid (GABA), which causes GABA-gated Cl-ion channels to open, thus working by hyperpolarising the nerve membrane potential and blocking the electrical nerve conduction (avermectins and emamectin) (Arena *et al*., 1995 and Feduchi *et al*., 1985). Polynactins can cause leakage of potassium ions from mitochondria (Feduchi *et al*., 1985).Herbicides inhibit phosphorylation in plants by blocking glutamine synthase, which causes an increase in ammonia (bilanafos) (Feduchi *et al*., 1985).Microalgae can be used as an alternative technology to increase productivity in sustainable agricultural systems. A number of microalgae strains produce biologically active compounds that include antimicrobial compounds with the potential to act as biopesticides (Gomiero., 2018 and Ranglová *et al*., 2021). The biomass (extracts) can be applied as an alternative to chemical pesticides (Gomiero., 2018 and, Costa et al., 2019) since it can enhance plant growth and protect agricultural crops (Costa *et al*., 2019). Microalgae have proved to be an excellent source owing to their advantages over traditional chemical pesticides. They produce a plethora of compounds with stimulating activities, including biomass and compounds, which can be used in the preparation of biopesticides, thereby enhancing crop protection Ranglová *et al*., 2021). Microalgae can be produced using wastewater, as they require nitrogen, phosphorus, and carbon and ammonium, which are abundant in wastewater, thus representing a nitrogen source. Biopesticides have several merits over conventional chemical pesticides. They are environmentally friendly, target specific, and not deleterious to nontarget organisms and hence potent enough to replace synthetic pesticides for pest management (Saberi *et al*., 2020).

Environmental impact of pesticides

When pesticides are administered to a specific area or plant by a farmer, they have the potential to migrate and degrade into the environment and using indigenous microbial strains and physicochemical factors. They show a variety of effects on non-targeted plants as well as kingdom animalia after entering into the ecosystem (Tudi et al., 2021). Pesticides are degraded in our ecosystem by a variety of physical and microbiological processes, including light, temperature, moisture, oxygen, and microorganisms. Pesticides degrade into new chemical entities called metabolites, which can be hazardous or non-toxic depending on their chemical composition (Liu et al., 2015; Marie et al., 2017). Pesticides and their metabolites are transported from a targeted to a non-targeted area *via* adsorption, leaching, volatilization, or surface runoff (Tudi et al., 2021). Because there is an attraction between soil particles and pesticides in sorption systems (attraction influenced by soil organic matter and soil texture), pesticides linger in the soil for a long period of time and have a harmful effect on the soil and ecosystem (Qin et al., 2014).

Physical and chemical properties such as molecular weight, ionizability, lipophilicity, polarizability, and volatility of pesticides decide their behavior and biological activity in soil (Bailey and White, 1970; Pignatello and Xing, 1995; Gevao et al., 2000; Beulke et al., 2004). In general, pesticide fate in a soil ecosystem depends on the abiotic transformation related to its physicochemical properties and also on biological transformation related to the presence of live organisms (Różański, 1992). The physical properties make them resistant, reducing losses while chemical structures determine the persistence of pesticides in soil or the environment. These physical and chemical properties of chemical compounds are linked to their movement in soil and aquatic systems and robustness under adverse conditions (Pereira et al., 2016). Some crucial processes, including adsorption, degradation, and movement, control the behavior and fate of pesticides in soil. Depending on how the pesticide moves, these processes are further classified into leaching, transmission, runoff, microbial and plant absorption. Pesticide transformations in the soil system may vary. Adsorption processes are based on physical forces such as van der Waals or chemical nature, such as electronic interactions (Gevao et al., 2000). Degradation of the pesticides leads to formation of free and bound residues with some altered molecular structures, which are difficult to extract (Roberts, 1984; Gevao et al., 2000). Through diffusion and volatilization, pesticides can dissipate into the atmosphere and wind or runoff leading to subsequent contamination of water bodies. The physical and chemical properties of soil and pesticides, along with other environmental conditions, are mainly responsible for their adsorption by target and non-target organisms, a phenomenon known as bioaccumulation. Chemical and physical characteristics have an impact on leaching, and vertical downward shifting from soil systems. Through the leaching process, pesticides can reach up to groundwater level, making water vulnerable to pollution. Leaching of pesticide into the groundwater in sufficient quantities can pose a hazardous risk to animal and human health.

The soil with a sandy nature and low organic content acted as an unstable holding system and weakly absorbed or persistent compounds were most likely to leach-out easily. The chemical, physical, and biological factors of soil with pesticides applied for agriculture practices may influence the leaching process (Steffens et al., 2013). The various agriculture practices are responsible for pesticides translocation in soil or water and the period of their persistence in that environment can be short or longer for weeks, months, or even years due to a number of factors, which include climate change, texture of soil, pH, temperature, moisture, and the content of mineral and organic compounds (Bailey and White, 1970; Gevao et al., 2000; Gupta and Gajbhiye, 2002). Additionally, the leaching and seepage of chemical compounds depends on their mobility as well as persistence, which increases the risk of water pollution (Pereira et al., 2016).

Pesticides are generally used to protect the crop, but there are several ways in which they can also contaminate the soil. Some of the common reasons include inappropriate use, a lack of information on how to use them in terms of amount, a high amount of runoff into water bodies, and pesticides that are adsorbed, desorb, and broken down during their passage through soil, and these phenomena are dependent on pesticide properties such as persistence, bio-accumulation, and toxicity. Because of this process, the soils become secondary sources of the pollutants with respect to air soil exchange (Pokhrel et al., 2018). According to the report, in European countries, the distribution of 76 pesticide residues was evaluated in 317 agricultural top soil samples, either they contained one pesticide or more than one (Silva et al., 2019). The bioavailability of pesticides in the food web, pesticide uptake, toxic kinetics, dispersion, metabolism, and excretion all has an impact on species. Pesticides are used excessively and arbitrarily on various crop species, causing harm to beneficial biota such as microorganisms, honey bees, predators, birds, plants, and small animals (Alengebawy et al., 2021).

Water is one of the essential elements for all forms of life on earth. About 71% of the water is covered by the earth's surface. Groundwater constitutes about 30% of the world's freshwater resources (Marsala et al., 2020). Groundwater quality is under threat due to fast population growth, urbanization, industrialization agricultural pesticides, and population stress (Jayaraj et al., 2016; Wagh et al., 2020). Pesticides may get into groundwater as a result of agricultural runoff from the field or even direct application. The presence of pesticides in water sources is a cause for worry. Pesticides are a type of hazardous chemical that poses a health risk to humans. In many places in the world, groundwater is the most significant source of drinking water. Pesticide pollution is generated from poorly managed agricultural operations and contaminates the surface and ground water. It reduces the quality of drinking water available (Khatri and Tyagi, 2015). The human body gets exposure to pesticides either directly or indirectly. By using pesticides on crops, humans come in direct contact with them and they affect the skin, eyes, mouth, and respiratory tract, and cause acute reactions such as headache, irritation, vomiting, sneezing, and rashes on the skin. The severity of these pesticides on humans depends upon exposure time and concentration. Generally, pesticides are released from the body in the form of excretion (urinary, biliary, and secretory gland). The consumption of such vegetables and fruits that are grown in pesticide contaminated soil and water used for long-term, accumulation increase the concentration of toxins inside the body organs and causes chronic diseases such as neurotoxicity, cancer, necrosis, asthma, reproductive disorder, cardiac disease, diabetes, etc. (Kalyabina et al., 2021). The quaternary nitrogen compounds such as paraquat are associated with neurodegenerative diseases like Parkinson's, but their molecular mechanism are still not well known (Franco et al., 2010). Similarly, pesticide group of carbamates inhibits the acetylcholinesterase (AChE) activity and is used as a biomarker of neurotoxicity (Gupta et al., 2016). The cancer problem is caused by the various pesticides, but breast cancer is the most common in all cancer types and is associated with organophosphorus (malathion and parathion) that affect cellular growth and proliferation (Calaf, 2021).

Biodegradation of pesticides is mainly mediated by using microbial systems. Microbes are able to produce a specific group of enzymes that are able to catalyze the pesticides from contaminated sites. The pure culture and mixed cultures of the bacteria and fungi were found to be effective in the removal of pesticide residues from the water and soil environment. Microbial consortium was found with superior degradation abilities (Bhatt et al., 2021c). Singh et al. (1999) found that microbes have developed a number of metabolic routes to breakdown or detoxify a variety of environmental contaminants, including pesticides. Conde-Avila et al. (2021) reported bacteria from the *genera Streptomyces, Flavimonas, Burkholderia, Micrococcus, Sphingomonas, Brevibacterium, Flavobacterium, Pseudomonas, Agrobacterium, Arthrobacter, Enterobacter, and Bacillus are associated with pesticide biodegradation*. There is a diverse group of bacteria and fungi that are capable of degrading pesticides. The different phyla include Bacteroidetes, Basidiomycota, Chlorophyta, Cyanobacteria, Actinomycetota, Firmicutes, and Proteobacteria. The bacteria that fall under

Actinobacteria have a tremendous capability to degrade several classes of chemical pesticides as most of the strains have high GC content and are actively used for the recycling of complex polymers. *Streptomyces*, *Nocardioides*, *Arthrobacter*, *Rhodococcus*, *Micrococcus*,and *Microbacterium* are members of the *Actinomycetota* phylum and can metabolize a variety of chemical compounds such as organochlorides, organophosphates, carbamates, triazinones, and others (Kim et al., 2017). Similar to this, firmicutes are essential to the biodegradation of pesticides. Of them, a few strains are known to be extremophiles because they have endospores that can withstand any harsh environment. Many firmicutes, such as Paenibacillus polymyxa, Bacillus licheniformis, Bacillus thuringiensis, Bacillus pumilus, Bacillus subtilis, and Bacillus cereus, have the ability to degrade insecticides (Patil et al., 1970). Furthermore, reports of the proteobacteria's ability to degrade pesticides have been made about α-, β-, and γ-proteobacteria. The following α-proteobacteria strains have been reported: Bosea, Mesorhizobium, Shinella, Ochrobactrum, Rhizobium, Methylobacterium, Azospirillum, Pseudaminobacter, and Sphingomonas. Furthermore, among the β-proteobacteria, the bacterial strains that have been reported are Ralstonia, Alcaligenes, Burkholderia, Achromobacter, and Cupriavidus. Additionally, among the γ-proteobacteria, Yersinia, Pseudomonas, Klebsiella, Acinetobacter, Serratia, and Xanthomonas have been described bacterial strains (Bhatt et al., 2020b; Kumar et al., 2021)

Discussion

Recent studies on biopesticides have demonstrated their effectiveness and environmental impact as a sustainable substitute for chemical pesticides. Because biopesticides are non-toxic, biodegradable, and environmentally friendly, they are safer for the environment and human health. Nevertheless, barriers to their widespread adoption include high costs, restricted availability, and regulatory barriers. More research and funding are required to get past these issues and encourage the use of biopesticides as a sustainable pest management solution.

Conclusion

One of the most difficult problems in the field of plant protection is finding alternative sources of compounds with pesticide activity. Renewable resources are crucial in overcoming resource constraints and mitigating environmental pollution. In addition to plants, other sources of bioactive compounds include the use of various wastes as a medium for microbial growth, which can also help to address the issue of increased waste production. Despite the fact that formulations and application techniques have advanced significantly, more research is needed to fully understand the use of biopesticides in plant protection, particularly with regard to the requirement for a regulatory framework to control nanomaterials that enter the food market.

Prospective investigations will focus on enhancing methodologies and conducting interdisciplinary studies to generate high-quality, affordable, safe, and efficient plant protection solutions.

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