Bio-pesticides and Biological Inoculants in Sustainable Agriculture

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Abstract

Natural, biologically based substances called biopesticides are used for plants in forests, gardens, farms, and other areas to manage different kinds of agricultural pests. Wide biopesticide forms have been developed from widespread origins. This chapter explains the benefits of biocontrol agents formed from plant-depend on substances, and microorganisms like bacteria, cyanobacteria, and microalgae. To manage manufacturing losses because of pest infestation, those techniques are mentioned, and corrections are offered for their software in cutting-edge agricultural operations. Due to their many numerous over chemical competitors, biopesticides are predicted to hold a large portion of the market soon. Microorganisms (fungi and bacteria) called bio-inoculants are utilized as bio-stimulators, bio-agents, bio-fertilizers, and stress regulators to increase crop productivity sustainably. This chapter also highlights the application of bio-inoculants in fruit and vegetable production.

Keywords: Biopesticides, Bio inoculants, Sustainable Agriculture, Adaptability, Beneficial Microbes

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1. Introduction

By 2050, it is predicted that there will be around 9.7 billion people on Earth, with Asia and Africa contributing the most to this growth (Kumar et al., 2021). Hence, It is necessary to increase production through sustainable agricultural practices and develop new, improved approaches to overcome these challenges and ensure food security Growing food production through the usage of compost and organic fertilizers, like biopesticides, or reducing the loss of yield owing to harsh circumstances in the environment (such as abiotic and biotic stresses) are only two examples of a way to boom agricultural productiveness (Pathak et al., 2018; Gonçalves, 2021). Abiotic stress can primarily be managed with bio-stimulants as well as bio-effectors (Van Oosten et al., 2017). Pest management tools and biopesticides are derived from organic materials or live microorganisms and make extravagant claims about their ability without compromising the quality of the final product to control yield losses (Saha et al., 2023).

Pesticides, which are applied on crops to prevent damage from infestations of agricultural pests, have a variety of side effects that pose risks to all living creatures. They are non-biodegradable (i.e., live within the surrounding for the long term) (Scholtz et al., 2002) and are famed to persuade malignancies (Nicolopoulou-Stamati et al., 2016). The market dominance of these synthetic pesticides, as well as their long-lasting inhibitory activity against pests, have a full-size effect on the manufacturing of commodities (Liu et al., 2021). From the research carried out through Business Communications Company (BCC), Inc., the marketplace for synthetic pesticides and biopesticides was anticipated to be worth USD 61.2 billion inside the year 2017 and is projected to reach USD 79.3 billion by the way of 2022 (Chen, 2018; Lehr, 2014). Crops grown on soils with high pesticide exposure often have lower nutritional values and a higher incidence of diseases and this is not ideal from the point of handling agricultural land to provide food and nutritional protection (Tripathi et al., 2020).

Biopesticides are chemicals or substances found in animals, flowers, and microorganisms like bacteria, cyanobacteria, and microalgae that are useful for manipulating agricultural pests and infections (Yousaf et al., 2024). Biopesticides are "formed from natural elements consisting of animals, plants, microorganisms, and definite minerals (Kumar et al., 2021b)." Products constructed from these biocontrol agents which include genes or metabolites, may be hired to avoid crop damage, according to the United States Environmental Protection Agency

(Seenivasagan and Babalola, 2021). Because of their host-specificity and environmental friendliness, the usage of biopesticides is significantly more likely than the application of their comparable, historic chemical pesticides (Essiedu et al., 2020). Argo-based compounds can be deployed in the agricultural sector much more effectively with the help of biopesticides to protect crop plants from diseases and invading pests (Chang et al., 2003; Essiedu et al., 2020).

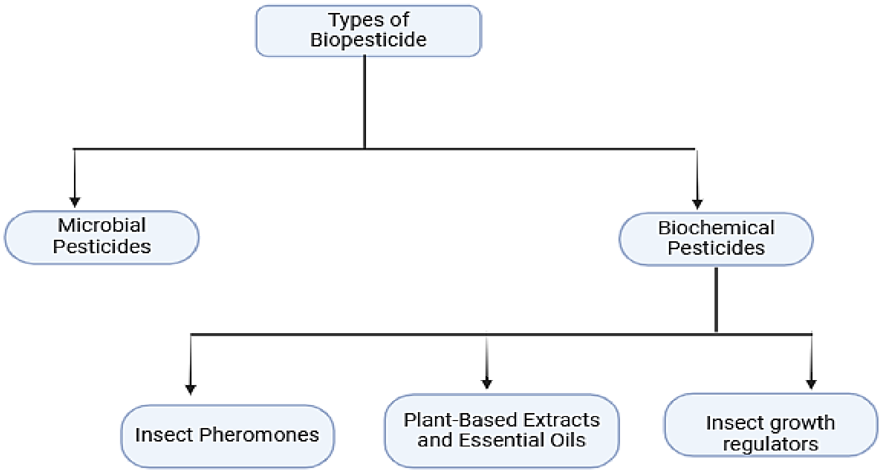

Fig. 1: Different types of biopesticides

1.2. Different Types of Biopesticides

Biopesticides come in an extensive variation of appearances and are categorized relying totally at the sources from which they're taken out and the molecules or compounds they are manufactured of (Ruiu, 2018). They can be categorized as follows.

1.2.1 Microbial Pesticides

These are created by microbes such as microorganisms, fungi, and viruses. Energetic compounds or substances of those organisms specifically target entomopathogenic nematodes or insect pests (Sarwar, 2015). Bioinsecticides specifically target insects that harm crops, as opposed to bioherbicides, which help to control weeds using microorganisms like fungi (Kumar et al., 2021b). An in-intensity examine of microbial biopesticides has brought about the invention and development of several biopesticides during the previous ten years and has additionally paved the way for their commercial viability (Ruiu, 2018). *Bacillus thuringiensis* and other microbial varieties have been successfully tested as pesticides, which has led to the invention of huge novel microbial species and traces, like launched toxins and harmfulness elements that could be useful for the biopesticide sector (Ujváry, 2010; Ruiu, 2018). Some of these have also been commercial products. Some bacterial species including Pseudomonas, Yersinia, Chromobacterium are well known entomopathogenic microorganisms. Few species of fungi i.e., *Beauveria, Metarhizium*, *Verticillium*, *Lecanicillium*, *Hirsutella*, and *Paecilomyces* also fell in this category (Sporleder and Lacey, 2021; Chang et al., 2003; Sporleder M., 2021). Baculoviruses, which have infectious traits linked to crystalline occlusion bodies and are species-specific, are active against eating insects i.e., Lepidopteran caterpillars, also known as important producers of microbial pesticides (Thakur et al., 2020). Recombinant Baculovirus (ColorBtrus) is produced when the Bt toxin and baculoviral blockage figure are joined. In contrast to its wild-type counterpart, this virus creates occlusion bodies that contain Bt insecticidal Cry1Ac toxin protein, growing its pathogenicity and change of motion (Chang et al., 2003). Entomopathogenic Nematodes (EPNs), which can be used as biocontrol agents, are critical of the genera Heterorhabditis and Steinernema. They're linked with mutualistic symbiotic microorganisms of the genera Photorhabdus and Xenorhabdus and are protected for mammals, the surrounding, and non-target species (Chang et al., 2003; Gulcu et al., 2017). Their proficiency in mass manufacture, enlist in vivo or in vitro methods, and freedom from enrollment have made their commercial improvement as biocontrol agents simply (Coupland et al., 2017).

1.2.2 Biochemical Pesticides

Biochemical pesticides employ organically taken place material to address pests appropriately, while chemical pesticides use artificial chemical compounds that directly kill insects (Hossain et al., 2017). Biochemical pesticides are in addition subdivided into several categories relying on how they lower insect pest infestations via pheromones (semi-chemicals), plant extracts/oils, or natural insect development controller (Kumar et al., 2021b).

1.2.2.1 Insect Pheromones

To control insects, integrated pest management strategies use substances that mimic those compounds generated by insects. These substances successfully inhibit insects from mating, hence reducing the number of offspring they produce (El-Shafie and Faleiro, 2017). The insects used in this technique operate as pheromone dispensers and get confused when pheromone flumes spread around them. Insect pheromones aren't real "insecticides" since they do not kill bugs however change the olfactory technique to change their manner (Gonzalez-Coloma et al., 2013). Several experiments have been performed to understand how the pheromones function (Ujváry, 2010).

In conclusion, pheromones are adsorbed by the antennae of the recognized insect, which permit them to dispense into the sensilla's indoors through opening inside the cuticle. Pheromone-binding proteins (PBPs) transport them once they have entered the cell through hydrophilic sensillum to the chemosensory layer. The pheromone or pheromone-PBP complex is subsequently bound by specific receptor proteins to transform the chemical sign into an elevated electric sign through a second messenger pathway related to neuronal equipment (Gurr et al., 1999; Kumar et al., 2021b).

1.2.2.2 Plant-Based Extracts and Essential Oils

Over the past few years, plant-based totally extracts and essential oils have emerged as acceptable options to synthetic insecticides for the manipulate of insect pests. Those naturally occurring insecticides considered they are derived from plants and contain a variety of bioactive additives (Magierowicz et al., 2020). Relying on the physiological features of insect species and the form of plant, plant taken out and vital oils may part as attraction, antifeedants, or repellents on insects. Furthermore, they can restrict breathing, prevent insects from admitting the vegetation of their hosts, stop oviposition, and reduce grown up emergence by having ovicidal and larvicidal movements (Ali et al., 2017; Halder et al., 2013). Their makeup differs substantially. Neem and lemongrass oils are excellent examples in this regard and are widely accessible in foreign herbal markets. Neem oil combined with entomopathogenic bacteria, such as *Beauveria bassiana*, was particularly effective against pests that feed on vegetables (Halder et al., 2013). Establishing the azadirachtin dose in neem oil is crucial to stop the eradication of non-target species (Mordue et al., 2010). For the entomopathogenic fungi to be effectively managed without harming nontarget insects, a comparable approach needs to be created and subsidized by supplementary testing site bioassays, station, and/or area studies (Dannon et al., 2020). Nearly, 45,000 tons of essential oils are produced throughout the World, with an estimated market value of USD 700.00 million. According to estimates, American firms can produce insecticides based on essential oils more swiftly than traditional pesticides (Parween and Jan, 2019).

1.2.2.3 Insect Growth Regulators

Insect growth regulators (IGRs) prevent insects from completing a few necessary life stages, which leads to their death. Additionally, these substances are very selective and less hazardous to creatures other than the targets (El-Sabrout, Hassan, & Eldesouky, 2019. IGRs have lately been divided into two classes depend on their modes of action: chitin synthesis inhibitors (CSIs) and compounds that block the consequences of insect hormones (including juvenile hormone analogues and ecdysteroids) (Gwinn, 2018). IGRs can control a wide range of insects, which include fleas, cockroaches, and mosquitoes, even though they are not mainly lethal to adult insects (Sarwar, 2020). They prevent immature insects from replicating, laying eggs, and molting among ranges even though they are no longer risky to humans. When applied along with other insecticides, they even can kill adult insects (Gwinn, 2018).

1.2.2.4 GMO Products

Those compounds are produced employing the usage of genetically modified organisms (GMOs). Genetic fabric is transferred to the crop and applied as an origin to make pesticides, regularly referred as plant-incorporated protectants (PIPs) (Abdollahdokht et al., 2022). The first-generation insecticidal PIPs, which were incorporated into GM plants and contained transgenes from the soil microorganism bacteria, were by far the biggest proteins (Parween and Jan, 2019). PIPs, in particular RNAi-based PIPs, also require continuous evaluation to determine how these molecules will behave in the environment (Parween and Jan, 2019; Parker et al., 2019).

1.3. Benefits of Biopesticides and their Comparison with Chemical Pesticides

The table above contrasts chemical pesticides with biological insecticides.

Chemical Pesticides	Biopesticides
Synthesized or produced from artificial means or chemicals meant to kill pests	Produced by the utilization of naturally occurring substances, originating from biological agents
Badly affects both the target and beneficial insects	Very specific to the target pest
Highly toxic to the environment and ecosystem due to continuous application in agriculture. Chemical substances can leach down in aquifers and cause infection of water bodies.	They are better than pesticides because they are non-toxic, safer for people, and have term long-term tolerance.
application increased, pests eventually turn out to be opposing e.g., Heliothis	Resistance is not constructed through pests.
Excessive-cost values and diminishing marketplace.	Relatively inexpensive than chemical pesticides; developing market option.
Resulting in bioaccumulation	Take away from inflicting bioaccumulation
Dangerous residues can also frequently be in food and fodder.	Residues of biopesticides are non-risky and no longer remain in food and fodder

1.4 Role of Biopesticides in Sustainable Agriculture

When it comes to managing crop pests, biopesticides have equal potential as synthetic pesticides (Rhoda et al., 2006). Natural materials are also advantageous from an environmental standpoint because they can be degradable more quickly than chemicals (Leng et al., 2011). Food made organically is in high demand and converting consumer tastes and willing to make biopesticides interesting alternatives to chemical pesticides (Okunlola and Akinrinnola, 2014). Since they have a very short pre-harvest period, biopesticides are risk-free to application on fresh fruits and vegetables (Khater, 2012). Additionally, they do not create any harmful impact on beneficial organisms, i.e., natural enemies because of their target-specificity (Tadele and Emana, 2017). They even work well in very small doses and lead to sustainable pest control, which helps sustainable agriculture (Nawaz et al., 2016).

Natural insecticides do not lead to the development of pest resistance (Tadele and Emana, 2017). They can be found naturally, and some are used for other functions like meals and food, thus for that reason their raw elements are widely available and cheap to buy (Srijita, 2015). The use of biopesticides is safe for each applicant and the consumer because they are non-toxic (Damalas and Koutroubas, 2016). Due to the existence of natural products and their quick decomposition, biopesticides can consequently be efficaciously incorporated into integrated pest management (Sesan et al., 2015) to lessen the number of chemical pesticides applied inside the control of agricultural pests (Kawalekar, 2013). Natural pesticides have exceptionally short re-entry intervals, which ensures the protection of an applicant (Stoneman, 2010). Through the introduction of significant microbial species, biopesticides can also be utilized to decontaminate agricultural soils (Javaid et al., 2016).

1.5. Bio-inoculants in Vegetable Production

Microorganisms (fungi and bacteria) are called bio-inoculants are utilized as bio stimulators, biocontrol agents, bio-fertilizers, and stress regulators to increase crop productivity in a sustainable manner (Tallapragada and Seshagiri, 2017). In today's vegetable production, bio-inoculants are being regarded as an alternative to chemical fertilizers. We had to enhance the yield of vegetables that is why the green revolution was necessary. Chemical fertilizers were used carelessly for this reason. Chemical fertilizers are costly, harmful to the surroundings, and the source of contamination in the soil, water, and air. Furthermore, they can eventually deplete the soil's fertility. These factors led scientists to discover that biofertilizers offer an alternative to chemical fertilizers. Microorganisms found in biofertilizers encourage the host plants to acquire a suitable quantity of nutrients, develop properly, and regulate their physiology (Kumar and Kumar, 2019).

1.5.1. Functioning of Bio-inoculants

- Facilitate atmospheric nitrogen fixation in soil and root nodules of leguminous crops, which makes nitrogen accessible to the plant.
- Conversion of insoluble phosphate forms, such as tricalcium, iron, and aluminum phosphates, into bioavailable formation for plant uptake.
- Phosphates are efficiently extracted from different soil strata.
- Synthesis of hormones and antimetabolites that stimulate and enhance root growth.
- Decomposition of organic matter

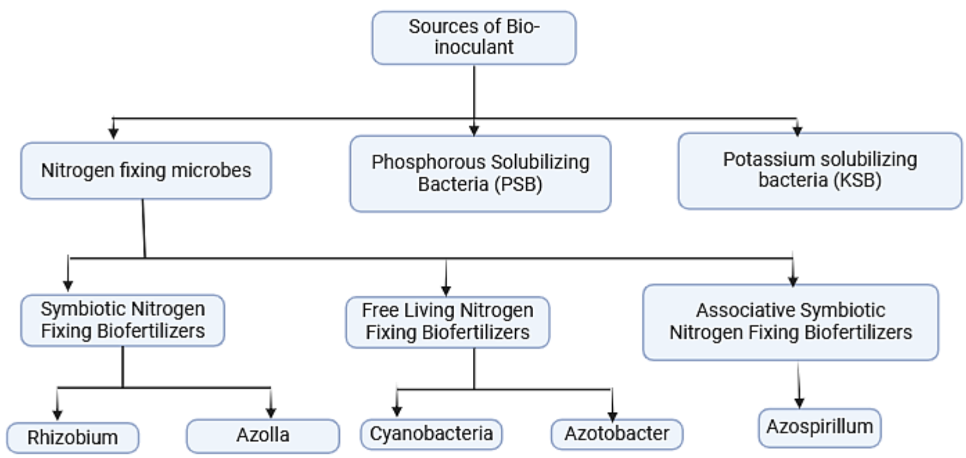

Fig. 2: Different sources of bio-inoculants

1.5.2. Different Sources of Bio-inoculants

1.5.2.1. Nitrogen-fixing microbes

The soil's microbiological activities are also enhanced by biological nitrogen-fixing bacteria. As a result, the plants grow and yield better. These microbes furthermore generate the hormones and different boom elements required for the nourishment and height of plants. These nitrogen-fixing microbes also eliminate several plant diseases. Both symbiotic and loose-residing nitrogen-solving microorganisms are crucial for reinforcing the soil's structure (Kumar and Kumar, 2019). Nitrogen-fixing microbes bio-inoculants are used as symbiotic, free residing, and associative symbiotic. Azolla and Rhizobium are instances of symbiotic nitrogen-fixing biofertilizers. Loose-dwelling nitrogen-solving biofertilizers include Azotobacter and Cyanobacteria (blue-green algae), like associative symbiotic nitrogen-solving biofertilizers as well as Azospirillum. In addition to this, there exist bacteria known as Phosphorus Solubilizing Bacteria (PSB) that fix or solubilize phosphorus (Singh and Verma, 2020).

1.5.2.1.1. Symbiotic Nitrogen Fixing Biofertilizers

1.5.2.1.1.1. Rhizobium

These are the well-known symbiotic nitrogen fixers, which are members of the Rhizobiaceae family and usually include several genera, including Rhizobium, Allorhizobium, Azorhizobium, Mesorhizobium, and Bradyrhizobium. Rhizobium are nonsporulating, motile, gram-negative rods that fix atmospheric nitrogen in a symbiotic manner. In the root nodules, Rhizobium aids in the reduction of molecular N_2 to NH_3, which is then easily absorbed by the plant roots. The complicated enzyme nitrogenase, which contains two enzymes—dinitrogenase reductase, which has iron as a cofactor, and nitrogenase, which has molybdenum and iron as cofactors—performs the N-fixation (Mahanty et al., 2017). Its ability to fix 50–100 kg of nitrogen per hectare annually makes it particularly helpful for determining the amount of N2 fixed. It is particularly important for legumes (Chaudhari and Barot, 2023).

1.5.2.1.1.2. Azolla

It is a diazotrophic symbiosis that can fix nitrogen from the atmosphere in tropical and temperate climates. The cyanobacteria Anabaena and Azolla have symbiotic interactions. Azolla contributes to the anabaena's carbon supply, and cyanobacteria's atmospheric nitrogen fixation meets the organism's nitrogen needs. Growing Azolla as a biofertilizer has the advantage of helping the plant meet its N and K needs (Singh and Verma, 2020).

1.5.2.1.2. Free Living Nitrogen Fixing Biofertilizers

1.5.2.1.2.1. Cyanobacteria

Cyanobacteria, sometimes known as "blue-green algae" or BGA, are tiny, unicellular, free-living, aquatic bacteria with the ability to produce their food through a process called photosynthesis. Nostoc, Anabaena, Calothrix, and Aulosira are the main nitrogen fixers among them; they are among the largest species of bacteria (Sahu et al., 2012). Vegetables like tomatoes, radishes, and spinach have benefited from cyanobacteria inoculation. It has been discovered that Anabaena and nostoc fix 20–25 kg of nitrogen per hectare (Singh and Verma, 2020).

1.5.2.1.2.2. Azotobacter

Azotobacter, a group of nitrogen-fixing bacteria, is a major biofertilizer that improves soil richness, yield-attributing characteristics, and vegetable production. It can fix an average 20 kg N/ha/year and produce thiamin, riboflavin, indole acetic acid, and gibberellins. When applied to seeds, Azotobacter improves seed germination and controls plant diseases. The exact mechanism of Azotobacteria's enhancement is not completely recognized, and three likely processes include N2 fixation, sending merge nitrogen, producing phytohormone-like substances, and bacterial nitrate reduction. Research has confirmed that Azotobacter strains increase sugar beet production and soil biogenicity. The usage of FYM 50% + Azospirillum 50% and Azotobacter 100% at optimum levels is beneficial in promoting crop growth, production, and quality (Kumar and Kumar, 2019).

1.5.2.1.3. Associative Symbiotic Nitrogen Fixing Biofertilizers

1.5.2.1.3.1. Azospirillum:

The utilization of biological products, particularly Azospirillum spp., has emerged as a novel technique for maximizing crop implantation. Azospirillum is a type of rhizobacteria that promotes root growth, which can colonize roots and improve plant uptake of water and minerals. Many scientific discoveries have been nicely documented that the utility of Azospirillum and different plant growth-promoting rhizobacteria better the plant progress and production of commercially remarkable crops like tomato, brinjal, and chilies. They live inside the roots of grasses and other related plants and are known as corresponding endosymbionts. They are also known to fix nitrogen from the atmosphere and help host plants by giving them vitamins and growth hormones. In general, the associative symbiotic bacteria Azospirillum helps non-leguminous crops, including horticulture crops, meet their nitrogen needs by increasing the production and nitrogen economy of vegetables (Kumar and Kumar, 2019).

1.5.2.2. Phosphorous Solubilizing Bacteria (PSB)

One important nutrient that is essential for crop growth and progress is phosphorus. It is not available to plants due to its extremely low bioavailability (Singh and Verma, 2020). Phosphobacteria (PSB) inoculation improves the solubilization of soil phosphorus and carries out phosphates, mainly to raise crop yields. That is because the stimulative impact of PSB is the supply of P solubilization, which will increase P availability and uptake via plants. PSB is a supply of P to plants upon release from their cells, relatable outcomes have been mentioned in tomatoes, cauliflower, turmeric, and peas. French bean, stricken by insufficient soil nutrient availability, calls for a big quantity of phosphorus for top quality increase and yield. Studies have proven that PSB remedy can enhance plant boom via increased phosphorus uptake, especially in low-fertility soils. Root inoculation with PSB 1:10 solution considerably will increase plant length, leaf place index, fruit range, yield, and yield per hectare (Kumar and Kumar, 2019).

1.5.2.3. Potassium solubilizing bacteria (KSB)

Numerous actinomycetes, fungal strains, and saprophytic bacteria are capable of dissolving potassium (Ahmad et al., 2016). There exists strong proof that soil bacteria can efficiently convert soil K into forms that plants can use (Meena et al., 2014). According to studies done in the past, KSB inoculation encourages the development of cucumber (Han and Lee, 2006), pepper, and eggplant (Han and Lee, 2005). Underneath greenhouse and area circumstances, the inoculation of seeds and seedlings of various plants with KSB often results in a considerable increase in the germination percentage, seedling vigor, plant growth, yield, and K uptake by plants (Anjanadevi et al., 2016; Awasthi et al., 2011). Additionally, the development of potatoes, eggplant, pepper, cucumber, okra, and brinjal was positively impacted by KSB inoculation (Han and Lee, 2005; Han and Lee, 2006). According to these studies, using KSB as biofertilizers to improve agriculture can lower the usage of agrochemicals and encourage the development of environment-friendly crops (Kumar and Kumar, 2019).

Future Prospective

Biofertilizers are gaining popularity in agriculture for enhancing crop yields and adapting to changing climatic situations. With the aid of reducing reliance on chemical fertilizers and improving soil health, the ability to apply plant increase-promoting rhizobacteria (PGPRs) as biofertilizers and biopesticides offers a wish for sustainable agriculture. Precision farming, which uses advanced technology to provide information on plant nutrient requirements and soil conditions, can maximize the usage of microbial inoculants by decreasing waste and increasing efficacy. Through plant adaptation to changing conditions, microbial inoculants can help lower the effect of climate change on agricultural productivity. Developments in genetic engineering and microbiology may result in the creation of novel microbial strains with enhanced functions, such as the ability to fix nitrogen in non-leguminous plants. Studies on phosphorus solubilization and nitrogen fixation have advanced more quickly than research on K solubilization by PGPRs. However, Microbial inoculants do have several drawbacks and challenges, such as a limited shelf life, the potential to lose efficacy if improperly handled, and difficulties in developing formulations with longer shelf lives. Researchers and enterprise professionals ought to look into techniques like selecting higher microbial traces, creating new foundations, standardizing quality manipulation, and teaching farmers and agricultural specialists about the blessings and suitable utility of microbial inoculants to conquer those demanding situations (Shahwar et al., 2023).

Conclusion

Via employing green generation, biopesticides made from microorganisms, cyanobacteria, or fungi can be applied to enhance and fill up soil fertility and guarantee sustained agricultural output. Applying microorganisms and microalgae as biopesticides can enhance the effectiveness of wastelands and agroecosystems while lowering power consumption and the want for artificial fertilizers. these organisms can make contributions appreciably to the synthesis of secondary metabolites, biofertilizers, bioenergy, and bioprocessed merchandise that could be beneficial in pest management when used alongside biotechnical breakthroughs like RNAi era to broaden the biopesticide business in the future, a top-notch deal of studies on biological manipulates sellers, which includes biopesticides, is essential.

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