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Review

Bacteria-Premised Nanobiopesticides for the Management of Phytopathogens and Pests

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ABSTRACT: Rising awareness of the risks regarding chemical formulations and the surging need for eco-friendly inputs in sustainable agriculture have driven the use of bacterial biocontrol agents to the frontline of plant protection. Bacterial biocontrol agents (BBCAs) have been preferred as feasible alternatives to synthetic formulations due to their increased specificity and safety. Nanotechnology has facilitated the better addressing of product development and performance concerns related to BBCAs. Leveraging nanotechnology in the synthesis of novel nanomaterials with amended properties at the nanoscale has offered efficient and ecologically sound nanoformulations such as nanobiopesticides. The nanobiopesticides of bacterial origin, known as bacteria premised nanobiopesticides (B-NBPs), are efficient alternatives to agrochemicals. The B-NBPs include living or nonliving bacterial nanoformulations or nanoparticles synthesized using bacteria (BNPs) as the nanofactories. The B-NBPs were synthesized using high-pressure homogenization (HPH), jet milling, and hammer milling, giving rise to competent bacterial nanoformulations of size ranging from 250 to 500 nm. Following an overview of bacteria-based nanobiopesticides (B-NBPs) employed to prevent/treat plant diseases, the article highlights the role of BBCA's role in plant protection as well as its antagonistic mechanisms. Further, the concept of B-NBPs, concentrating on *Bacillus thuringensis*-driven forms, is reviewed. The review then briefly explains the significance of BNPs in plant infection management. Finally, the concerns related to the efficacy of B-NBPs along with the prospects are also described.

KEYWORDS: *biocontrol, nanobioformulations, plant protection, bacillus thuringensis, pests, phytopathogens*

1. INTRODUCTION

Numerous advancements in the agriculture sector make a substantial contribution to the economies of many nations.[1] Population growth and shifts in climatic conditions have intensified the need to enhance agricultural food production to cater to the increasing consumer demand. The green revolution, predicated primarily on synthetic crop protection agents like chemical pesticides and fertilizers, brought about significant changes, including improved productivity, decreased yield reduction, etc. Pesticides/fertilizers are chemicals utilized to prevent plant diseases and control pests. The most prevalent effective ingredients (EIs) in these chemicals include organophosphates, carbamates, chlorinated hydrocarbons, and derivatives of carbamide.[2] These agrochemicals have drawbacks such as increased content of organic solvents, limited dispersibility, and dust drift.[3]

Furthermore, they are reported to be carcinogenic,[2] cause prenatal abnormalities,[4] and are nonbiodegradable.[5] Owing to their hazardous effects, conventional pesticides leveraged for crop protection and containing pathogens in farmlands pose various protracting perils to living beings. Eventually, many pests and pathogens acquire resistance to the agrochemicals employed to eliminate them,[6,7] entailing the extended use of existing chemicals or the development of novel, presumably more toxic, chemicals. The overuse of these resources has resulted in serious soil, surface water, and groundwater pollution, adversely affecting the environment. Thus, environmentally acceptable alternatives with limited pesticide wastes, reduced toxicity, and production expenses are imperative.[3]

The emphasis has been on creating nontoxic and environmentally sustainable substitutes to agrochemicals for pest and disease control to ensure long-term agricultural output.[8−11] Traditional tactics in agricultural operations, such as integrated pest control, are inadequate, prompting a desire for alternatives.[12,13] Biological control agents meet these criteria, enabling them as a viable solution to synthetic chemicals.[14,15] Biological control agents or biocontrol agents (BCA)[16−19] are naturally occurring compounds or producers of plants, animals, microorganisms, specific minerals, etc., that are capable of combating plant pathogens and pests.[5] In terms of geography, the global BCA market has five major regions: North America, Europe, Asia Pacific, Latin America, and the Middle East and Africa (MEA). Europe and North America are the market leaders for BCA. BlueWeave Consulting,[20] a leading strategic consulting and market research firm, in its latest report, estimated the size of the global biological control agents market size at USD 4.32 billion in 2021.[20] During the forecast period

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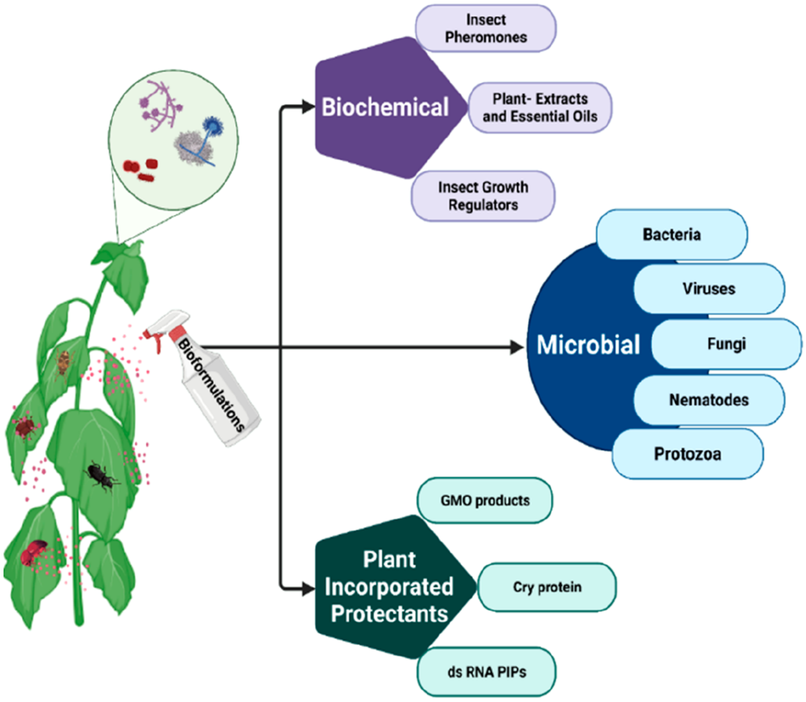

Figure 1. Classification of various biopesticides utilized for the management of different insect-pest species and phytopathogens.

between 2022 and 2028, Blue Weave expects the global BCA market size to grow at an impressive compound annual growth rate of 15.1% to reach a value of USD 11.48 billion by 2028.[21,22] Similarly, according to Maximize Market Research,[23] a private firm specializing in business and market research in multiple disciplines including agriculture, the Global BCA Market was worth US$ 2.83 billion in 2019 and is anticipated to grow at a CAGR of 13.5% by 2027, reaching US$ 7.79 billion. As reported by Maximize Market Research Private Limited,[23] North America has a significant share of the international BCA market. This is owing to the widespread recognition and acceptance of these products among farmers.[22]

Bacteria constitute one of the most substantiated biological control agents that are capable of utilizing numerous mechanisms to hinder plant diseases. The bacterial biocontrol agent (BBCA) is capable of lowering the phytopathogen/pest population by multiple mechanisms, such as direct antibiosis, competition, hyperparasitism, etc. In this article, biopesticides relate to the diversity of BBCAs employed to regulate phytopathogens/pests and protect plants. As biopesticides, several bacterial-based products have previously been registered and commercialized.[24] Nonetheless, greater initiatives are necessary to expand the number of bacterial biopesticides that are commercially accessible. The unpredictability of the efficacy of BBCAs has impeded their widespread application in agricultural production.

Nanotechnology permits the synthesis of materials with amended properties/functionalities at the nanoscale. The use of nanomaterials as carriers of agrochemicals has enhanced application efficiency and lower dose requirements.[25] Through the emergence of nanobiopesticides (NBPs), nanotechnology establishes the improved efficacy of BBCAs and thus improved global crop production. NBPs in the context of the review could be defined as nanostructures involving either very small particles of a BBCA or other small engineered structures derived from BBCAs with antagonistic activity against plant pathogens/pests.[26−31] The functional molecules or delivery components employed in these NBP formulations are at the nanoscale. These nanosized particles outperform typical pesticides due to their smaller size, which assists in appropriate insect surface distribution. Owing to their compact size, these NBPs excel the conventional agrochemicals in terms of better penetration into plant cells and improved insect surface dispersion.[26] Furthermore, when employed as a delivery agent, it shields BBCAs from undesirable environmental conditions like high temperature, excess rainfall, etc., with their significantly increased chemical stability. It also improves the BBCA formulation's dispensability and wettability and offers an intelligent delivery platform with sustained release at the intended site.[32] NBPs are an emerging technology that offers great potential in the fight against agricultural pests/pathogens. They are natural, eco-friendly substitutes to traditional agrochemicals that are made up of nanomaterials, such as nanoparticles and nanocapsules. These nanomaterials are designed to contain and deliver active ingredients such as enzymes, proteins, and other bioactive molecules that target specific pests. NBPs can be used as direct applications or as part of integrated pest management strategies, which can help reduce the amount and types of chemical pesticides used. Thus, integrative multidisciplinary strategies of employing nanosystems for efficient delivery of EIs/BCA are crucial.

The review introduces the concept of bacteria-based nanobiopesticides (B-NBPs) and their application in the management of plant diseases caused by diverse plant pathogens and pests. Primarily, we discuss the relevance of BBCA in plant protection together with the main mechanisms involved in the antagonistic nature of BBCAs. Furthermore, we describe the various approaches of B-NBPs, emphasizing *Bacillus thuringensis*-driven NBPs. Then, we outline the notion of bacteriogenic nanoparticles (BNPs) and their significance in the mitigation of plant infections. Lastly, we conclude by exploring the concerns as well as future trends related to the efficient utilization of NBPs together with their safety implications.

2. SIGNIFICANCE OF BACTERIAL BIOCONTROL AGENTS (BBCAS)/BIOPESTICIDES IN PLANT DISEASE MANAGEMENT

Living systems or their products reduce plant pathogens and pests to facilitate the biological management of plant diseases (Figure 1).[33] BBCA, referred to as a biopesticide, is one such approach that acts *via* various modes for the biological control of phytopathogens and pests.[34] Bacteria belonging to the genera such as *Bacillus*, *Rhizobium*, *Serratia*, *Agrobacterium*, *Xanthomonas*, *Pseudomonas*, *Alcaligenes*, *Streptomyces*, *Erwinia*, *Arthrobacter*, *Enterobacter*, etc., have been identified as prospective candidates for mitigating plant diseases and developing NBPs.[24,35] Among these, bacteria from the genera *Streptomyces*, *Bacillus*, and *Pseudomonas* have been explored extensively, and several are currently registered and commercialized. There are currently 13 bacteria-premised BCA registered as biopesticides in the EU for the suppression of phytopathogens/pests (Table 1).[24]

Table 1. List of the Several Bacteria-Premised BCA Registered As Biopesticides in the EU[a]

genus	species/sub species	strains
Bacillus	*amyloliquefaciens*	• QST 713
		• AH2
		• MBI 600
		• FZB24
		• IT 45
	amyloliquefaciens subsp. *plantarum*	• D747
	Firmus	• I-1582
	pumilus	• QST 2808
	subtilis	• IAB/BS03
Pseudomonas		• DSMZ
	chlororaphis	• MA 342
Streptomyces	*griseoviridis*	• K61
	lydicus	• WYEC 108

[a] Prepared as of June 1st, 2022 based on https://food.ec.europa.eu/plants/pesticides/eu-pesticides-database_en.[24].

They either indirectly kill pests/pathogens by discharging siderophores or directly by creating crystalline proteins, resulting in a shortage of resources required for the survival of pests/pathogens.[33] One significant benefit of using BBCA is that they are environmentally safe, easily degraded, and thus leave no harmful residues.[36] The rationale behind the recent upsurge in the use of BBCAs include (i) resistance of pests to synthetic pesticides, (ii) decrease in the rate of discovery of novel insecticides, (iii) rise in public awareness of the environmental concerns related to agrochemicals, (iv) host-specificity of BBCA, and (v) advancements in BBCA manufacturing.[37] The BBCA are self-regulating and thus do not require complicated management, impart minimal toxicity on plants, are effective for long-term disease management, and influence plant growth favorably.[38] Hence, they could be the finest feasible solution to harmful synthetic agrochemicals.

2.1. Bibliometric Analysis and Relevance Study. The application of BCAs (Figure 2A) and BBCAs (Figure 2B) in pest and plant disease management appears to be rapidly expanding, as revealed by the significant rise in research published between 2012 and 2020. The bibliometric data for BCA were retrieved from the SCOPUS database (https://www.scopus.com/, extracted on March 20, 2023) utilizing specified keyword search biocontrol AND agents OR microorganisms OR plants OR plant AND protection, yielding 1968 publications. The bibliometric data for BBCA were derived from the SCOPUS database (https://www.scopus.com/, obtained on March 20, 2023) again using particular keywords like bacteria AND based AND biocontrol AND agents OR microorganisms OR plant AND protection, generating 153 documents. The bibliometric assessment was accomplished using several bibliometric indices, such as the most prevalent keyword phrases, nations, and research groups, and was generated using the VOSviewer processing program (VOSviewer version 1.6.18) (Figure 2). For acquiring a detailed outlook of the prevailing investigation in this field, network analysis (Figure 2A1,B1), cluster density visualization (Figure 2A2,B2), and overlay analysis (Figure 2A3,B3) of information on BCA and BBCA were conducted.

2.2. Mechanism of Action of Bacterial Biocontrol Agents (BBCAs) against Pests and Pathogens. BBCA employs a broad range of strategies to defend plants against pathogen/pest invasion (Figure 3). They either utilize one or a combination of tactics to avoid or eliminate plant disease, appealing to the pathogen directly or indirectly.[33] BBCA may engage in direct antagonism by secreting antimicrobials, meddling with virulence, and competing for resources and space. Certain BBCAs secrete antimicrobial secondary metabolites like iturin, fengycin, surfactin, bacteriocins, cell-wall disintegrating enzymes, etc., and thereby curb the colonization of pathogens.[39,40] BBCA also may impact the pathogens' quorum sensing (QS) systems by deteriorating or reducing the production of signal molecules required to launch infections. For instance, the synthesis and release of QS blockers including lactonases, glucanases, pectinases, lyases, and chitinases, which disintegrate QS signal compounds, diminish pathogen invasion and manifestations of plant disease.[41]

Furthermore, BBCA may reduce pathogen load by competing with pathogens and lowering their multiplication rate without eliminating them. Hypercompetitive bacterial BBCA may proliferate and persist in the infected area, and they could possess an effective mechanism for absorption of nutrients than the pathogen, for example, discharging low-molecular-weight siderophores having ferrous iron affinity.[42] They also potentiate direct encounters with pests/pathogens *via* antibiosis or hyperparasitism. Hyperparasites invade and damage bacterial and fungal pathogens' cells and resting structures (mycelium, spores, etc.).[43]

Outside of direct antagonistic interaction, BBCAs protect plants indirectly through the mechanism of stimulating the plant defense system to elicit amplified resistance to plant infections caused by pests/pathogens.[34] This leads to the formation of structural barriers and the activation of several biochemical and molecular defensive reactions in the host, protecting against a broad spectrum of pathogens/pathogens.[44,45] Additionally, BCA may stimulate plant growth by promoting mineral and water uptake or synthesizing molecules that drive plant growth such as hormones, hence improving plant health and vitality. Thus, antagonistic microbes can limit pathogen populations *via* different modes. The environment, risks of acquiring resistance, pathogen specificity, etc., might vary. Preferences regarding specific modes of action for the intended use of a BBCA will also impact the screening processes used to identify novel antagonists.[34] The aspect of the mode(s) of action determines both characteristics and the impact of the antagonist on the

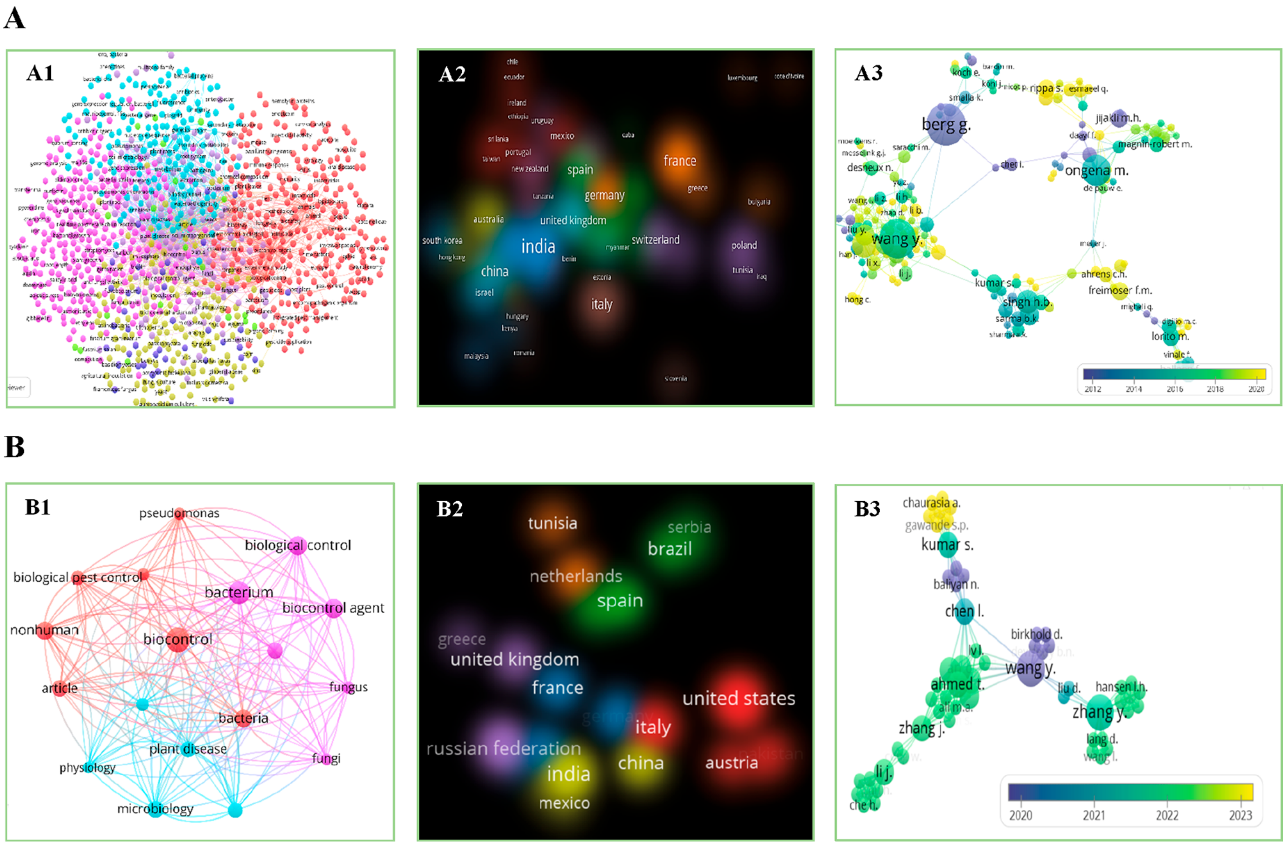

Figure 2. (A) Bibliometric analysis of 1968 articles published on biocontrol according to the Scopus database using specific keywords such as biocontrol AND agents OR microbes OR plants OR plant AND protection: (A1) network analysis of their worldwide distribution, (A2) cluster density visualization; the larger the circle the more intense the scientific activity, and (A3) overlay analysis of the groups working on the same. (B) Bibliometric analysis of 153 articles published on biocontrol according to the Scopus database using specific keywords bacteria AND based AND biocontrol AND agents OR microbes OR plant AND protection: (B1) network analysis of their worldwide distribution, (B2) cluster density visualization; the larger the circle the more intense the scientific activity, and (B3) overlay analysis of the groups working on the same. The data evaluated using VOSviewer version 1.6.18 accessed on March 2023.

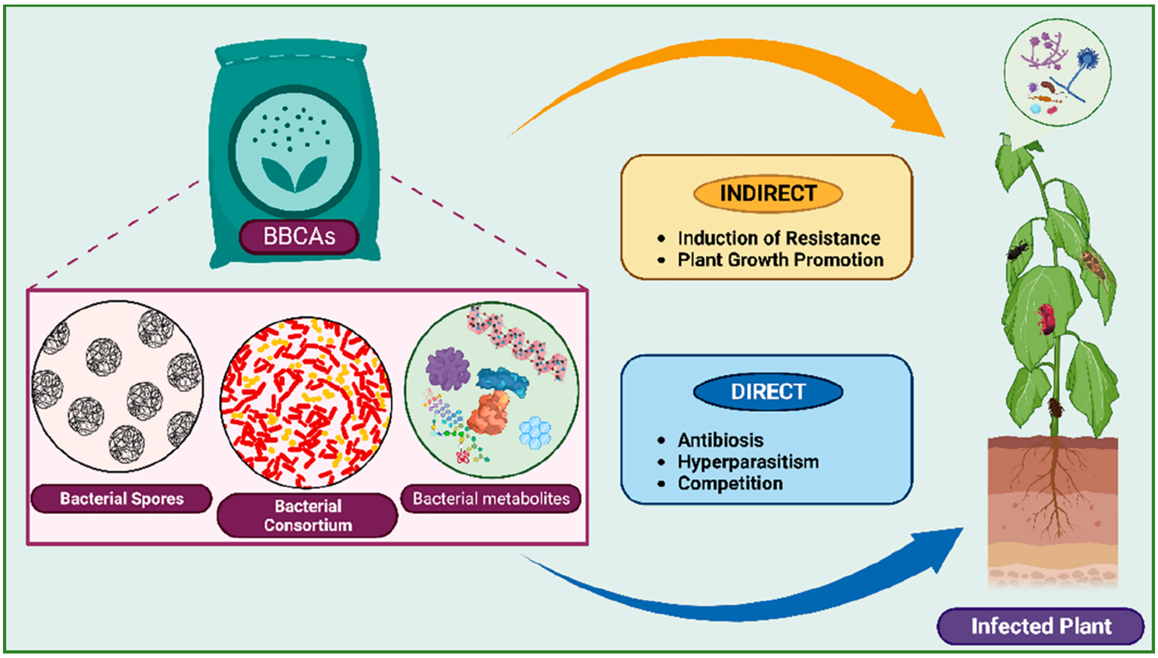

Figure 3. Schematic representation of the major mechanism of action adopted by BBCAs to protect the plant from phytopathogens/pests.

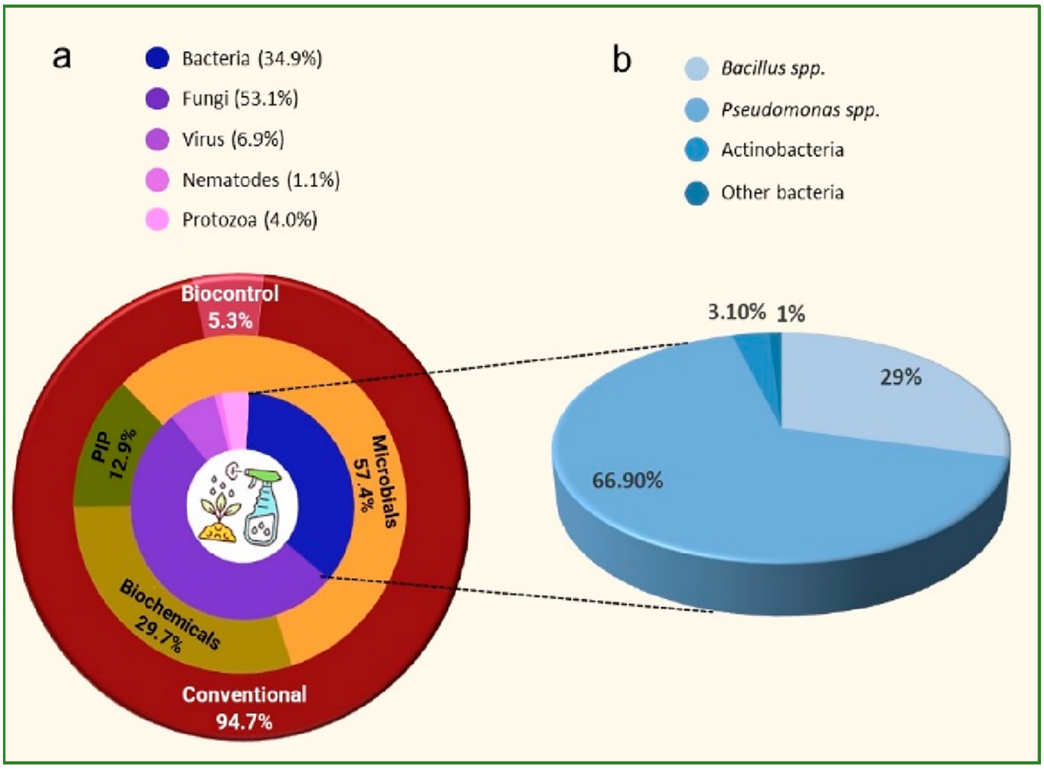

Figure 4. Statistics on the numerous biocontrol agents (BCA) utilized for plant protection on a global scale. (a) Outermost layer of the doughnut chart depicts the current proportion of conventional and biocontrol agents employed worldwide. The center layer illustrates the major types of BCA used for plant protection. The innermost layer represents the various kinds of microbial BCA deployed.[106,174−176] (b) Pie graphic represents the percentage of specific biopesticides among the diverse microbial group of BCA.[33,176,177]

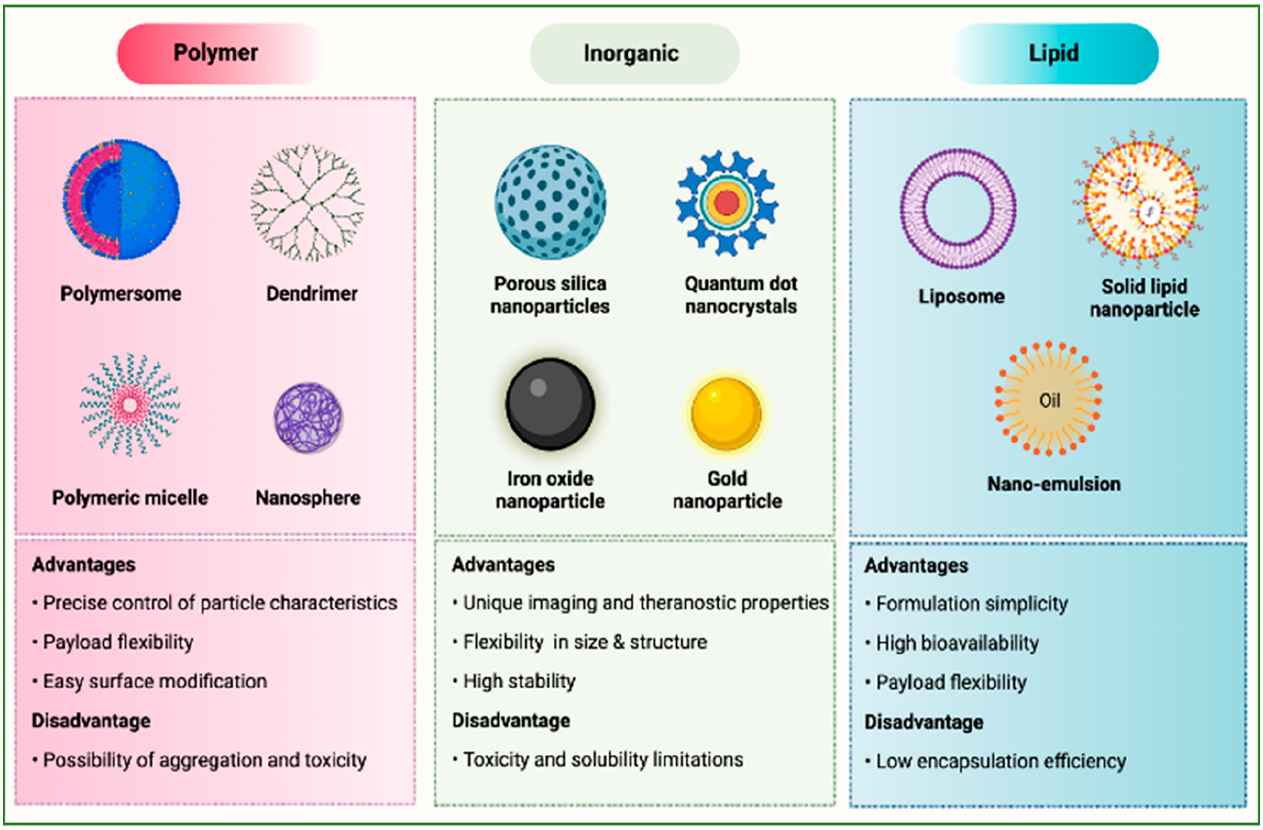

Figure 5. Prospective nanomaterials employed as smart delivery platforms of distinct biopesticides and development of NBPs.[178−182]

Table 2. Summary of the Various BBCAs and their Application in Plant Protection

BBCA	strain	mechanism/compound involved in protection	target pest/pathogen	dosage	application	ref.
Bacillus amyloliquefaciens	PPBOO4	Iturin/Fengycin/Bacillomycin D	*Alternaria citri, Botrysphaeria sp., Colletotrichum gloeosporioides, Fusicoccum aromaticum, Lasiodiplodia theobromae, Penicillium crustosum, Phomopsis persea*	10^8 CFU·mL^{-1}	20–70% inhibition of disease incidence in fungi infesting oranges	80
B. subtilis	ABS-S14	cyclic lipopeptide antibiotics, L-phenylalanine ammonia-lyase, peroxidases.	*Penicillium digitatum*	10^6 CFU·mL^{-1}	suppressing postharvest fruit decay caused by *Penicillium* in mandrins	81
B. thuringiensis subsp. *aizawai*	2387	spores, toxins, cry proteins	*Pieris rapae, Plutella xylostella, Heliothis virescens*	300-fold diluted insecticidal formulation	spawns 77–90% larval mortality in the target pests infesting cabbage and tobacco plants	82
B. mojavensis	B0621A	mojavensin A, iso-C16 fengycin, anteiso-C17 fengycin B	*Fusarium graminerium, Rhizoctonia solani, Botrytis cicera, Colletotrichum orbiculare*	1 mg·mL^{-1} of isolated compounds	exhibited potential antifungal activity toward a multitude of fungal phytopathogens	83
B. pumilis	MAIIIM4A	pumilicidin	*Rhizoctonia solani, Pythium aphanidermatum, Sclerotium rolfsii*	10^8 CFU/mL	control of infection caused by multiple fungal plant pathogens	84
Paenibacillus popilliae		hyper parasitism	*Popillia japonica*		effective in inhibiting the infestation of *Prunus*, *Tilia*, and *Larix* plants	85
Lactobacillus plantarum	TC92, PM411	low pH of lactic acid and competitive exclusion	*Pseudomonas syringae, Xanthomonas fragariae, Xanthomonas arboricola*	10^8 CFU·mL^{-1}	45–75% protection of kiwifruit, *Prunus*, and strawberry from multiple bacterial pathogens	86
Streptomyces	CBQ-EA-2, CBQ-B-8		*Macrophomina phaseolina, Rhizoctonia solani*		mitigation of ashy stem blight and Rhizoctonia blight of *Phaseolus vulgaris*	87
S. lydicus	MO1	antibiosis and nutrient competition	*Alternaria alternata*	2×10^8 CFU·mL^{-1}	control of foliar diseases in cucumbers	88
Pseudomonas chlororaphis	PCL1606	2-hexyl, 5-propyl resorcinol	*Rosellinia necatrix, F. oxysporum* f. sp. *radicislycopersici*	10^9 CFU·mL^{-1}	protection against white root rot in avocado and tomato	89
Pseudomonas simiae	PICF7	induced resistance, stimulation of plant defense enzyme	*Verticillium dahliae*	10^8 CFU·mL^{-1}	20–28% verticillium wilt disease management in the root of olive plants	90
Leuconostoc mesenteroides	CM135, CM160	Class IIa bacteriocins	*Listeria monocytogenes*	1.3×10^4–5.0×10^5 CFU·g^{-1}	efficient and safe bioprotective agent against *L. monocytogens* in Golden Delicious apple and Iceberg lettuce leaves	91

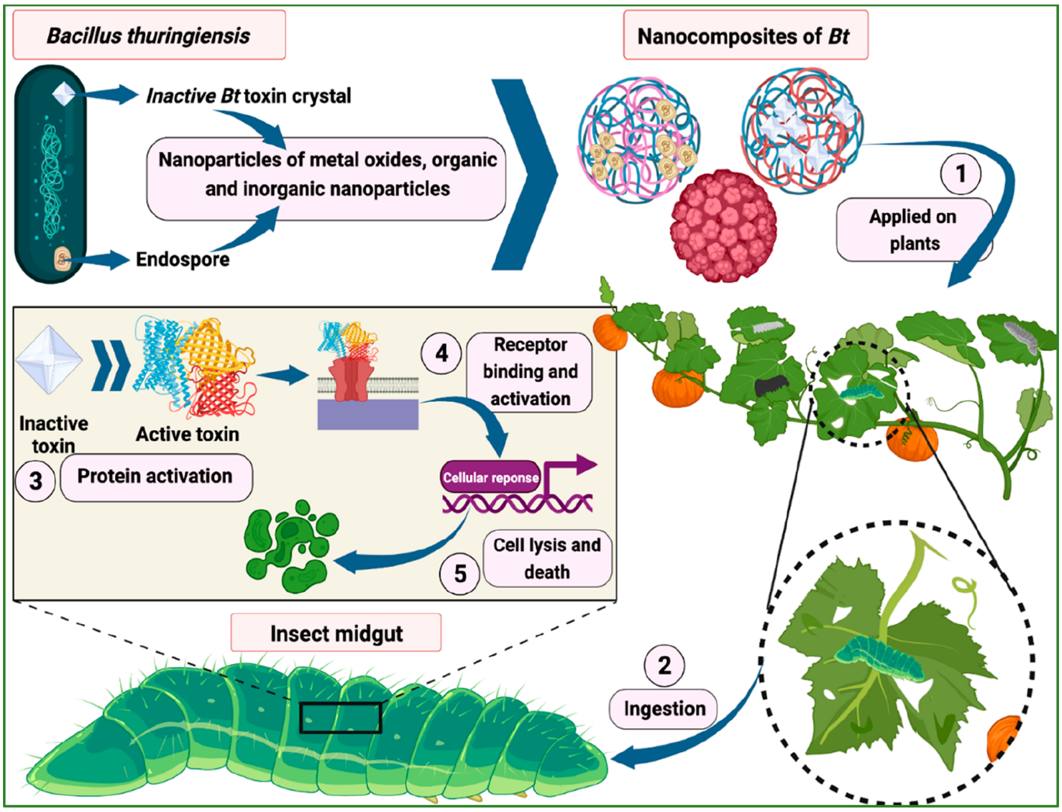

Figure 6. Mode of action of B-NBPs derived from *Bacillus thuringensis* against various lepidopteran insect pests.[81,130,183]

pathogen population. Depending on the mechanism of action, the major implications on the population or the environment, risks of acquiring resistance, pathogen specificity, etc., might vary.

3. NANOBIOPESTICIDES: AN EFFICIENT BIODEGRADABLE APPROACH FOR PLANT DISEASE MANAGEMENT

The term "nanobiopesticide (NBP)" in connection to the review refers to the coupling of the environmentally benign BBCAs derived from natural sources for crop protection purposes and the biocompatible nanomaterials used either as EIs or for creating NBPs.[46] Briefly, they are nanostructured BBCAs/biopesticides leveraged to combat pests and pathogens affecting plants. Owing to their low pest resistance and minimal detrimental effect on the environment, sustainable and green NBPs derived from natural products create an avenue for combating pests and phytopathogens.[47] Nevertheless, NBPs account for a minor portion of the whole global plant protection sector, with an approximate value of $3 billion, representing about 5% of the overall sustainable agricultural industry (Figure 4).[48]

The application of NBPs is increasing by almost 10% every year worldwide.[48−50] However, NBPs are yet to acquire the level of application necessary to surpass their chemical equivalents. Stability, field applications, and delivery strategies are all areas of concern.[50,51] Although low retention of biopesticides can be beneficial where environmental residues are an issue, there remains a risk that it might not elicit the intended impact in regulating phytopathogens and pests. Other downsides of biopesticides include higher cost, low activity, short shelf life, and performance volatility application.[31] The application of nanotechnology to managing plant diseases holds potential, primarily in substituting agrochemicals with natural agents while preserving productivity and efficacy.[52−56] Thus, researchers are striving to develop NBP formulations for plant pathogens/pests for plant protection that are comparable to traditional formulations but have better properties such as greater solubility, delayed release, and are not prematurely degradable.

This emerging sector of agricultural nanotechnology comprising nanostructuring of biopesticides facilitates a better understanding of the interface between weeds/pests/phytopathogens and nanoscale materials. It also entails the incorporation of biopesticides into nanoemulsions and dispersions and the production of novel B-NBPs utilizing nanomaterials as active pesticide agents or nanocarriers for their delivery.[28−30] The nanostructuring of biopesticides permits the enhancement of their physicochemical parameters, such as solubility, resilience, permeability, crystallinity, thermal stability, and biodegradability, in comparison to the existing ones. Figure 5 depicts the frequently employed nanomaterials involved in the nanostructuring of biopesticides and the production of NBPs as well as the limits and benefits they are likely to pose. These multifunctional organic and inorganic nanocarriers have enabled the efficient delivery of diverse biopesticides through their increased ability to encapsulate and permit the gradual release of the biopesticides into the soil.[57−59] Importantly, coupling nanocarriers with biopesticides permits controlled or sustained release, better efficiency, and the utilization of lower dosages of the biopesticide. The large surface area offered by NBPs increases the affinity to the target species/groups and reduces the amount of biopesticide required for pest/pathogen control.[60] Similarly, recent studies have focused on the implementation of nanotechnology to augment biopesticide efficacy and reduce losses owing to physical deterioration (such as volatilization and leaching).[61−63]

4. BACTERIA-DERIVED NANOBIOPESTICIDES (B-NBPS) AS PLANT PROTECTION AGENTS

Bacteria are unicellular prokaryotes with distinctive physiological, morphological, and evolutionary attributes.[64,65] They could be used to combat pests and phytopathogens. Bacteria used as BCAs or BBCAs belong to four major categories,[66,67] namely, crystalliferous spore formers,[19,68−70] obligate pathogens,[71,72] potential pathogens,[73,74] and facultative pathogens.[75−77] BBCAs are a widely utilized microbial biological control (MBCA) that works in various ways for the eradication of pests. The two significant prerequisites to achieving efficacy are interaction and ingestion by the potential pests. Table 2 lists the most commonly used bacteria and their function as plant protection agents. Bacteria ingested by insects impede digestion by producing endotoxins causing the death of the insect pest.[78,79]

Bacteria-premised nanobiopesticides (B-NBPs) are a type of NBP that utilizes beneficial bacteria or their components to control pests/pathogens. These types of NBPs can be either living or nonliving and can be used to control a variety of pests, including insects, nematodes, and plant pathogens.[92] One example of a living B-NBP is *Bacillus thuringiensis* (Bt), which is used to control a wide range of lepidopteran pests, including moths and butterflies.[93] The average particle size of nanosized Bt was observed to be between 250 and 500 nm, with a minor fraction of particles falling below 1 μm. Besides, nonliving B-NBPs pertain to the inclusion of bacterial spores, metabolites, and enzymes such as lipopeptides or chitinases in ecologically viable nanocarriers and their deployment for plant protection.

A significant proportion of insect pathogenic bacteria are found in the Bacillaceae, Enterobacteriaceae, Pseudomonadaceae, and Streptococcaceae families.[94] As MBCAs Bacillaceae members, particularly *Bacillus* spp.,[68,95−97] have garnered great attention. The Bacillaceae family constitutes Gram-positive, rod-shaped, heterotrophic, endospore-forming bacteria. *Bacillus thuringiensis*,[98,99] *B. sphaericus*,[100] *B. popillae*,[71,72] *B. pumilus*,[101] *Brevibacillus laterosporus*,[102] among others. *Bacillus thuringiensis* (Bt) is a prevalent soil-borne bacteria capable of producing spores and crystals during the stationary phase of its development.[36] The majority of the crystals are composed of various δ-endotoxins—Cry and/or Cyt having antagonistic activity against specific insect pests infesting plants (Figure 6). Each variant of Bt produces and secretes unique type toxins that attack pests belonging to a particular taxon. Therefore, toxins synthesized by Bt protect crops against significant pests such as *Plutella xylostella*, *Lymantriidae ninayi*, *Helicoverpa armigera*, *Callosobruchus maculatus*, *Ostrinia nubilalis*, *Spodoptera frugiperda*, *Agrotis ipsilon*, *Spodoptera exigua*, etc.[103,104] Amidst Bt's great target selectivity and eco-sustainable green properties, the Bt pesticide market accounts for only 1% of the worldwide plant protection sector yet 97% of the global MBCA industry.[105] Early Bt products failed to compete with chemical pesticides owing to low performance, despite their beneficial attributes. Commercial research concentrated on two schemes to tame these obstacles: (i) augmenting the synthesis of Bt products *via* the development of novel techniques and (ii) strain improvement to enhance the bacterium's innate lethality.[40]

In addition to the formulation, the method of manufacture and stability of the biomass of the BBCA are also important factors, which affect the efficacy of *Bacillus*-based products in the field. Spray coverage on foliage will be improved due to the small particle-size distribution.[106] Liquid suspensions were the simplest to manage but had limited shelf life, whereas powders were convenient to transport as well as store, but curing/reformulation was costly and cumbersome for the consumer. Nanostructuring of the formulation resolved these concerns. This prevented suspensions from settling and hence a rise in shelf life. Nanotechnology also helped incorporate UV screening agents that could resist rapid photolysis of the biocontrol agent after spraying.[30,107] These enhancements, coupled with stricter quality standards and validation of potency screening, could contribute to a 6-fold or greater[31,108] upsurge in ineffectiveness in the field. Regrettably, the use of *Bt* nanoparticles (*Bt* NPs) in plant protection is an elusive goal that remains to be addressed. There is minimal data available about research into enhancing efficiency through the generation of *Bt* NPs.

4.1. Microionization-Driven Synthesis Nanobiopesticidal Formulations of *Bacillus thuringiensis* (*Bt*). Top-down initiatives for microionization, such as high-pressure homogenization (HPH), jet milling, and hammer milling, leveraged for converting coarse particles to superfine powders, are utilized to create *Bt* in nanoform. Using these approaches, the average particle size was determined to be between 250 and 500 nm, with a tiny percentage of particles dropping below 1 μm.[109] Although these strategies facilitate easy scale-up, batch-to-batch fluctuation in extraction and contaminations resulting from milling balls restrict their application.[110] In addition, the heat produced by the high-speed milling process may diminish the vitality and efficacy of *Bt*. As a result, milling must be performed while assisted with cooling.[111]

Few studies have attempted to enhance the functionality of *Bt* by reducing the size of *Bt* powders using a top-down strategy. These studies have been limited to hammer and/or air milling techniques and HPH.[105,111,112] *Bt* powder homogenization in water has shown great promise. Kim and Je[112] in 2012 revealed that a homogenized *Bt* suspension with smaller particles outperformed an unblended spray-dried powder of *Bt aizawai* NT0423 in regulating diamondback moth infestation in plants. After 2 min of homogenization in water at 6000 rpm, the particle size was effectively reduced from 37.1 to 1.9 μm. Notably, the larval mortality of the diamondback moth was 78.3% 2 days after treatment (DAT) with homogenized *Bt* suspension and 27.5% with unmilled powder. Analogously, the mortality rate of larvae 3 DAT was 100% (homogenized *Bt* suspension) and 72% (unmilled powder). Comparably, Murthy et al.[113] proved that homogenization in water *via* HPH could significantly decrease the size of *Bt* powder particles from 105 μm to 32−1000 nm. Furthermore, in laboratory conditions, they observed a progressively higher larvicidal effect of *Bt* NPs, at 50% reduced doses than the unblended *Bt* powder. Compared with the unblended *Bt* powder, the overall alkali-soluble protein and Cry protein of *Bt* NPs increased 2.18- and 2.24-fold, correspondingly. This was attained even though the number of heat-viable dormant spores in unhomogenized *Bt* powder was greater when compared with those in *Bt* NPs. The enhanced larval mortality of *Bt* NPs was attributed to a greater dissolution rate of the toxin in the midgut. The ensuing proteolytic stimulation rendered the toxin more accessible for interacting with the surface receptors of the alkaline midgut cells, resulting in immediate immobility and subsequent paralysis of midgut cells.[113]

Hammer milling and air-jet milling were two other methods adopted for the reduction of the size of *Bt* particles. Kim and Je[112] indicated that hammer milling failed to reduce the particle

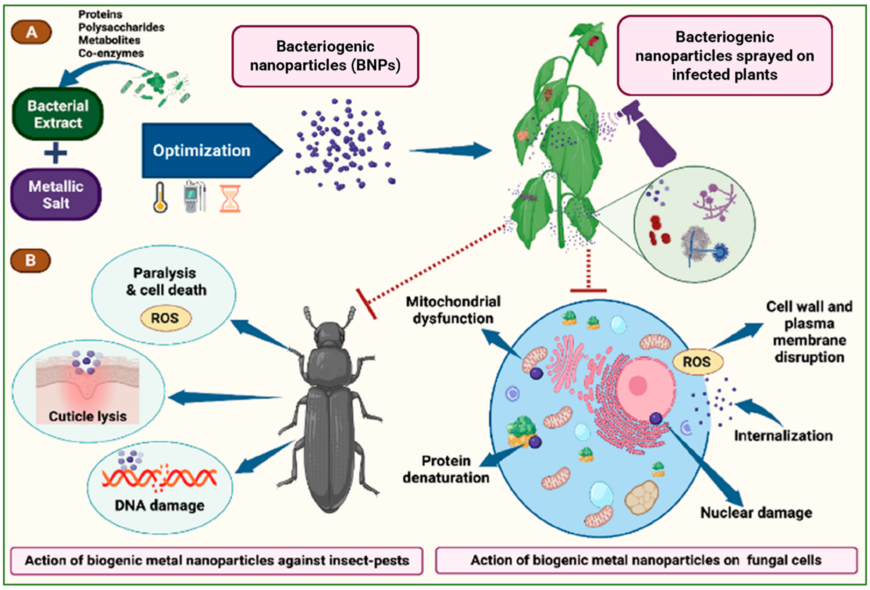

Figure 7. (A) Synthesis of biogenic metal nanoparticles from bacteria and (B) their mode of action in regulating insect pests and phytopathogenic fungi.

size, whereas air-jet milling was capable of lowering it to 5.3 μm. Conversely, Vineela et al.[111] were fruitful in achieving *Bt* powders with particle sizes ranging from 105 μm to 210 nm with hammer milling. Total alkali-soluble protein was greater at 153–175 mg/g in milled *Bt* powders than that in unmilled *Bt* powder, depicting a clear correlation to particle size. As opposed to unmilled *Bt* powder, all the samples of milled powders contributed to high fatalities of third-instar *Spodoptera litura* larvae. Hence, microionization represents a promising approach to enhancing *Bt* efficacy, but its commercial viability is yet to be investigated. Alternatively, it is also required to evaluate the possibility of directly delivering protoxins to the host plant for their rapid stimulation midgut, as the initial phase of crystal solubilization could be conquered.

4.2. Nanocomposites of *Bacillus thuringiensis* (*Bt*) as Prospective NBPs. Bt nanocomposite EIs like crystals coupled with metal oxide nanoparticles might function as UV protectants for Bt, considerably enhance effectiveness and storage stability, reduce dose, and conform to nanotechnology norms. There ought to be some mechanism in Bt-based nanocomposites to preserve both activities without limiting their effectiveness as nanobiopesticides. This field is also underexplored, and much effort is needed before its application.[114] Additives encapsulated in nanoparticles containing *Bt* through various nanoformulations, including nanoemulsion, nanosuspension, and nanocapsules, can enhance the reliability and residual action of Bt, potentially increasing its field efficiency and application.[48,115−117] A Bt formulation equipped with graphene oxide nanosheets(GONs) shielded the Bt from high temperature and UV radiation. The formulation strengthens the capability of olive oil as a Bt UV filter agent. The integrated formulation spawned a 68.89% larvicidal effect in the population of the Mediterranean flour moth *Ephestia kuehniella*, whereas free spores caused 40% lethality in the larvae.[118] At a 25 g/Ml dose, Bt-coated zinc oxide nanoparticles were 100% lethal to the *Callosobruchus maculatus.*[119] Nanosized Bt chitinases incorporated silica nanoparticles (Bt SNPs) contributed to increased pH tolerance, thermostability, and UV resistance ability, while cohesively enhancing Bt's nematicidal effects. This was verified on the nematode *Caenorhabditis elegans* was suppressed by the Bt SNPs with a lower lethal dose and at a shorter lethal period.[120] Additionally, micro- and nanotechnology are utilized to treat Bt strains requiring enhanced protection, fortification, and dispersion in the field. Tamez-Guerra et al.[121] researched the insecticidal activity of Bt spore toxin microencapsulations against *Trichoplusiani* and revealed elevated residual insecticide action in *Brassica oleracea* var. capitata. Bt parasporal crystal protein packed with nano-$Mg(OH)_2$ efficaciously amended the protein's larvicidal activity, protected the structure of the protein from damage, and increased resistance to UV.[122] Under environmental conditions, nanoencapsulation of Bt (HD-703 and HD-95) primed through HPH of 2.53% surfactant and approximately 98.79% glycerol greatly inhibited *Tuta absoluta*.[105]

5. BACTERIOGENIC NANOPARTICLES (BNPS) AS B-NBPS FOR PLANT PROTECTION

Owing to their unique morphology (shape and size), which is controlled by biological, chemical, and physical variables, nanoparticles have recently received significant interest in the disciplines of biology and medicine. Nanoparticles generated from chemical synthesis were shunned in the food and pharmaceutical industries due to the toxicity of the chemical agents employed in their synthesis. A preferred technique for the production of nanoparticles should offer materials that are better encapsulated, provide cost-effectiveness, and contain no toxic components.[123] Green syntheses of nanoparticles mediated by bacteria against pests and microbes affecting plants has opened up new avenues for the design and synthesis of biogenic nanoparticles. These biogenic nanoparticles are nontoxic and economical when compared to traditional pesticides in use.[124−126]

The nanoparticles synthesized using bacterial enzymes/metabolites/proteins as the reducing/capping agent are known as bacteriogenic nanoparticles (BNPs). The primed biosynthesis of such BNPs occurs in two potential sites intracellular and extracellular (Figure 7A).[127] The BNPs are reported to demonstrate strong antagonistic activity against

Table 3. Application of Several Biogenic Nanoparticles Synthesized by Bacterial Species

bacteria	biogenic nanoparticles	morphology	target pathogen	application	ref.
Deinococcus radiodurans	Au NPs	spherical, triangular and irregular shapes	*Escherichia coli*, *Staphylococcus aureus*, *Penicillium* spp.	show detrimental effects on the cytoplasmic membrane of pathogenic bacteria	140
Bacillus siamensis C1	Ag NPs	spherical	*Xoo strain* LND0005, *Acidovorax oryzae* (*Ao*) strain RS-1	potential in preventing bacterial leaf blight and brown stripe infections on rice plants, as well as promoting plant growth	141
B. amyloliquefaciens,	Ag NPs	spherical	*Culex pipiens pallens*	spawns rapid larval mortality in vectors and is also active against pathogenic bacteria	142
B. thuringiensis coating	ZnO NPs		*Callosobruchus maculatus*	*Bt*-ZnO-based nanoparticles regulate the cowpea seed beetle population.	119
B. cereus RNT6	ZnO NPs		*Burkholderia glumae*, *B. gladioli*	effective in the management of rice panicle blight-causing bacteria	131
Paenibacillus polymyxaI Sx3	ZnO NPs, MnO_2 NPs, MgO NPs	polymeric shapes	Xoo strain GZ 0006	exhibits antibacterial activity against bacterial leaf blight of rice plants, while improving the production yield	143
Lactobacillus rhamnosus	Ag NPs	spherical, triangular, rod, and hexagonal shaped	*L. monocytogenes*, *K. pneumonia*, *P. aeruginosa*, *Aspergillus*, *Penicillium*, and *Candida* spp	exhibited antimicrobial and antibiofilm efficacy against food-borne bacteria and fungi as well as multidrug-resistant pathogens	144
Lactobacillus casei subsp. *casei*	CuO NPs	spherical		could be employed as plant growth stimulation by providing micronutrients	145
Geobacter sulfurreducens	Ag NPs	triangular	Gram-negative bacteria	applied in conjugation with other biocontrol agents	146
Pseudomonas poae CO	Ag NPs	spherical	*Fusarium graminearum* PH-1	suppresses spore germination, germ tube growth, and mycotoxin generation and causes cell membrane damage to *Fusarium*	147
Streptomyces griseus	Cu NPs	spherical	*Poriahypolateritia*	efficient nanometallic fungicide used for the mitigation of red rot disease in tea plants	148
Streptomyces pseudogriseolus ACV-11	Ag NPs	spherical	*Alternaria alternata*, *Fusarium oxysporum*, *Pythium ultimum*, *Aspergillus niger*, *Culex pipiens* and *Musca domestica.*	mitigation of several phytopathogenic fungi and insect pests	149
Stenotrophomonas sp.	Ag NPs	spherical	*Sclerotium rolfsii*	prevented conidial germination but also triggered the defense mechanism in chickpeas by causing phenolic acid/hydrogen peroxide production and alteration in lignification	150
Pseudomonas rhodesiae strain G1, *B. amyloliquefaciens* strain A3, and *Paenibacillus polymyxa* strain ShX304	AgNPs	spherical	*Dickeya dadantii*	curbed soft rot diseases in sweet potato plants by causing cessation of swimming, inhibition of biofilm formation, and maceration in potato tubers	151

plant-infecting pests and pathogens through various mechanisms (Figure 7B).[126,128] In the case of extracellular synthesis, the metal salts are reduced by the bacteria when supplied extracellularly and the color change explains the production of BNPs. Whereas, nanoparticles synthesized intracellularly can be isolated by disruption of cell membranes *via* heat shocks or sonication.[129] Due to the availability of several reductase enzymes that may convert metal salts to metal nanoparticles (MNPs), bacteria are significant nanofactories that can accumulate and detoxify heavy metals.[126]

The extracellular method was used to create silver nanoparticles (AgNPs) from the *Bacillus* strain GP23 isolated from the coastal area, which inhibited *Fusarium oxysporum*, the ascomycete fungus causing the wilt disease of legumes, bananas, cucurbits, and tobacco.[130] Extracellularly generated AgNPs from the *Bacillus* strain SBT8 exhibit antibacterial characteristics and function as biocatalysts.[123,131] Nanoparticles were produced by combining silver nitrate with *B. subtilis* and *B. amyloliquefaciens* protected plants against several bacterial and fungal pathogens displayed specifically *Candida albicans.*[123] The nanocrystallization of cyclic lipopeptides derived from *B. subtilis* enhances storage stability by inhibiting oxidation and antifungal action by the regulated administration of cyclic lipopeptides. Additionally, these cyclic lipopeptide nanocrystals (solid lipid nanoparticles) suppress the development of *Aspergillus carbonarius*, *A. fumigatus*, and *A. niger* spores as well as hyphae.[132] The zerovalent AgNPs generated utilizing *Bacillus* spp. strain AW1−2 greatly diminished the population of *Colletotrichum falcatum*, the pathogen causing sugar cane red rot.[131] A few of the several types of biogenic nanoparticles synthesized using bacteria are listed in Table 3.

Besides AgNPs, copper- and zinc-based nanoparticles have also been used effectively against phytopathogens. Copper oxide nanoparticles (CuONPs) produced by *Streptomyces capillispiralis* Ca-1 were effective against both bacterial and fungal (*Alternaria alternata*, *Pythium ultimum*, *F. oxysporum*, *A. niger*) strains. The size of the nanoparticles ranged from 3.6 to 59 nm, and their FTIR analysis revealed the presence of bioactive compounds that might have attributed to the antimicrobial effects.[133] Copper nanoparticles (CuNPs) isolated from *Streptomyces griseus* were used to prevent the red root diseases in tea plants caused by *Poria hypolateritia.* The CuNPs had a size of 30−50 nm and were produced as a result of the reduction of copper by protein or enzymatic reactions in *S. griseus.* The developed nanoparticles were on par with the commercially available fungicides.[134] Zinc oxide nanoparticles (ZnONPs) derived using bacteria have also been widely studied for their activity against various plant pathogens. ZnONPs are advantageous over the classic antifungal agents as their use does not affect soil fertility.[135] ZnONPs also aid in the prolonged contact between the bacterial cell membrane and nanoparticles, thus causing increased bactericidal activity. ZnONPs isolated from the Gram-negative heterotroph *Aeromonas hydrophila* demonstrated excellent activity against pathogenic bacterial and fungal strains such as *P. aeruginosa* and *Aspergillus flavus*, respectively.[136] *A. flavus* affects oil seed crops by producing aflatoxin before and after the crop harvest.[137] Hence, the use of ZnONPs could prevent the growth of the pathogen in oil seed crops without harming the crop health. Furthermore, the design, development, and application of BNPs have been extensively discussed elsewhere[128,138,139] in addition to the recent studies presented here.

5.1. Bacterial metabolites for Synthesizing BNPs.

Bacteria deploy intracellular and extracellular systems to synthesize nanoparticles. In the intracellular method, the bacterial cell acts as a transporter, and the negatively charged bacterial cell attracts positive-charged metal ions *via* electrostatic attraction. Further, the enzymes of the cell wall aid the metal ions in being dipped into the nanoparticles. In the extracellular method, biosorption of the metal ions onto the bacterial cell aids in nanoparticle synthesis and diminishes with the extracellular enzyme secretion.[152]

5.2. Bacterial Enzyme-Mediated Synthesis of BNPs.

Bacterial enzymes act as dipping mediators in the synthesis of nanoparticles. The role of dipping factors is mainly performed by NADH (nicotinamide adenine dinucleotide) and reduced form of NADH-reliant enzymes by the electron transport between NADH and NADH-reliant enzymes.[153] The study of gold nanoparticle (AuNPs) synthesis by *Rhodopseudomonas capsulate* revealed that NADH and NADH- reliant enzymes mediated the process. The AuNPs are synthesized due to the reduction of Au^{3+} to Au^0. Hydroquinones, anthraquinones, and naphthoquinones are the other compounds widely exploited for nanoparticle synthesis.[154]

5.3. Bacterial Pigment-Mediated Synthesis of BNPs.

One of the active areas of research in nanotechnology is microbe-mediated nanoparticle synthesis. Several microbes have been known to synthesize nanoparticles,[155] but microbes take a long time to grow and reduce metal ions to nanoparticles.[156] However, bioactive molecules such as enzymes, pigments, proteins, etc., have been widely exploited for the rapid, reliable, and green synthesis of nanoparticles. Pigments are one of the primary metabolites of bacteria used in the synthesis of medically relevant nanoparticles.[157158]

5.4. Engineered Nanomaterials from Bacteria.

AgNps were synthesized by Kanmani and Lim[159] from *Lactobacillus rhamnosus* GG, a lactic acid bacterium, and tested their efficacy against pathogens in food and the ones causing multidrug resistance. The initial process involved the production of exopolysaccharide (EPS). The bacteria were incubated at 37 °C for 18 h in DeMan, Rogosa, and Sharpe agar broth (MRS) and heated to 100 °C for 15 min. Debris and probiotic cells were removed by centrifugation and the supernatant obtained was mixed with 95% ethanol and incubated for 12 h at 4 °C. The precipitated EPS was washed and mixed with $AgNO_3$. Sixty days of incubation of the mixture followed by a 10 h incubation resulted in the formation of engineered nanomaterials (ENMs), which was indicated by the formation of a yellowish solution. The synthesized nanoparticles had a size range of 2−15 nm and shapes of spheres, triangles, and hexagons. ENMs showed antibacterial activity against *E. coli*, *L. monocytogenes*, and multidrug-resistant pathogens such as *P. aeruginosa*, and *K. pneumonia*.[159] Photosynthetic bacteria *Rhodo-pseudomonas capsulate* was used to synthesize ENMs from gold. The bacteria were initially let to mature in an appropriate growth media and then were incubated with chloroauric acid. Spherical ENMs with a diameter of 10−20 nm were synthesized.[160]

6. INVENTIVE POTENTIAL OF B-NBPS FOR PLANT PROTECTION

B-NBPs are an innovative and novel form of pest and pathogen control that promises to revolutionize how plant diseases are managed and eradicated. The application of these NBPs is an exciting prospect due to its potential to reduce the reliance on traditional chemical control methods, which can be hazardous and detrimental to the environment. B-NBPs are created by combining bacteria with nanosized particles, such as silica or carbon, in order to create a tiny, microscopic plant disease mitigation agent. The bacteria are chosen for their ability to produce substances that are toxic to the targeted pest/phytopathogens, and the nanoparticles are added to the bacteria to increase their effectiveness. This combination of bacteria and nanoparticles results in a plant disease mitigation agent that is much smaller than conventional agrochemicals, which makes them easier to apply and less likely to drift or spread to unintended areas. The administration of B-NBPs is relatively simple and easy to manage. The nanoparticles are mixed with the bacteria and then applied to the infected area. Additionally, they can be applied in ways that reduce the amount of pesticide residue left on crops, reducing the risk of contamination. The nanoparticles provide a protective layer around the bacteria, which helps to prevent the bacteria from being washed away by rain or other forms of precipitation. This protective layer also enables the bacteria to stay active and effective for a longer period.

Polysaccharides such as alginate, gelatin, and chitosan have been widely used for the encapsulation of bacteria promoting plant growth to counteract several plant-pathogen induced diseases.[161−164] Riseh and Pour[165] developed a microcapsule loaded with *Streptomyces fulvissimus* Uts22 to control *Gaeumannomyces graminis* var. *tritici*-induced take-all disease in wheat. The microcapsules of chitosan-gellan gum loaded with *S. fulvissimus* Uts22 had a size of 140−150 μm. The *S. fulvissimus* Uts22 loaded in the microcapsules demonstrated an enhanced inhibitory effect against *G. gramimis.* Furthermore, the survival of encapsulated *S. fulvissimus* Uts22 was estimated to be 10^8 CFU g^{-1} after 60 days of storage at room temperature. The release of the bacteria from the sprayed microcapsules into the soil was sustained with a maximum release at day 50 (10^9 CFU mL^{-1}) with 90% disease control efficiency.[165] Similarly, Saberi Riseh et al.[166] shaped microcapsules loaded with *S. fulvissimus* Uts22 to control damping-off disease caused by *Pythium aphanidermatum* in cucumber. The microcapsules were developed using a layer-by-layer technique consisting of alginate-Arabic gum and nanoparticles of SiO_2 and TiO_2. The developed microcapsules had a cubical shape with a size ranging between 140 and 150 μm. The microcapsules also showed an inhibitory effect against *Pythium aphanidermatum.* The encapsulation efficiency of the bacteria into the microcapsule was found to be 94%, and the maximum release of bacteria was observed on day 35 (10^9 CFU g^{-1}) after storage at room temperature. Greenhouse experiments showed a 95% reduction in the disease with enhanced plant growth.[166] Recently, Pour et al. developed microcapsules made up of alginate together with whey protein, plant-derived gums plus SiO_2 and TiO_2 nanoparticles. The as-prepared microcapsules were led with *Bacillus velezensis* against plant pathogens. Here, *Gaeumannomyces graminis* var. *tritici* was the model plant pathogen in consideration for various experimental studies. The developed microcapsules had an almost cubic structure, as observed in SEM, and they exhibited excellent antifungal activity against *Gaeumannomyces graminis* var. *tritici.* The encapsulation efficiency was observed to be 94.33%, and the release profile of the bacteria from the microcapsule was maximum at day 50 after incubation at room temperature.[167] Pour et al.,[168] in 2021, synthesized a nanocomposite bead composed of alginate-gelatin, loaded with *Bacillus velezensis* VRU1, against *Rhizoctonia solani* in the bean plant. The synthesized nanocomposite beads were measured to be 150 m in diameter. Further release studies indicated that the maximum release of bacteria from nanocomposite beads was recorded to be on day 35, and after which, the release profile declined. Greenhouse experiments revealed a 96.33% disease control achieved by the established nanocomposite beads.[168] The use of plant growth-promoting Rhizobacteria by encapsulating them for reducing salinity stress in plants has been discussed in detail elsewhere.[169] The suppression of *Fusarium solani*-mediated infections in potatoes utilizing nanocomposites of alginate-gelatin was reported by Pour et al., in 2019.[170] The alginate-gelatin nanocomposite loaded with *Pseudomonas fluorescens* (VUPF5 and T17-4 strains) presented excellent inhibitory effects against *F. solani.* Notably, with an increase in gelatin content, the nanocomposites created exhibited greater encapsulation. Maximum encapsulation was obtained at 1.5% gelatin in the nanocomposite, with VUPF5 and T17-4 encapsulated at 91.23% and 87.23%, respectively. In potatoes treated with the VUPF5 and T17-4 strains as well as nanocomposites, a significant reduction in disease incidence was revealed. The frequency of infection was reduced by 76% and 75%, respectively, when nanocomposites containing VUPF5 and T17-4 were employed.[170] Correspondingly, alginate-gelatin nanoformulation with carbon nanotubes and SiO_2 was produced to deliver *Bacillus velezensis*, for the mitigation of Pistachio gummosis disease caused by *Phytophthora sp.* SEM analysis revealed the globular structure of the nanoformulation with a large size variation. The as-synthesized formulation containing *B. velezensis* was effective against *P. drechsleri.* Moreover, the encapsulated bacterial formulation achieved notable postencapsulation survivability (10^7 CFU mL^{-1}) and remained stable after one year of storage.[171] Alginate microbeads encapsulated with *Pseudomonas fluorescens* VUPF506 for the management of *Rhizoctonia solani* in potatoes were synthesized by Fathi et al.[172] in 2021. The microbeads were nonuniform with a porous surface. With a 90% pathogen suppression efficacy, the controlled release of the bacteria from as-prepared microbeads was proven to remain for over two months.[173] In 2021, the same group encapsulated the VUPF506 strain of *Pseudomonas* in a microcapsule of alginate-whey protein with carbon nanotubes. The capsules were prepared by three different techniques: spray drying, extrusion, and emulsification, and the encapsulation efficiency was detected to be 80% in extrusion and emulsification techniques. The size of microcapsules varied according to the type of synthesis technique employed, for instance, extrusion (150−250 μm), drying (1−10 μm), and emulsification (50−150 μm). Besides, *Rhizoctonia* infections in potatoes were prevented by 70% due to the newly designed microcapsules.[172]

In addition to their ease of use, B-NBPs are also more environmentally friendly than chemical pesticides. This is because they do not contain any harmful chemicals, such as insecticides and herbicides, which can cause damage to the environment. Furthermore, as the bacteria are only active in the proximity of the targeted pest/phytopathogen, there is less risk of the bacteria drifting and spreading to unintended areas. This makes them a much more targeted and precise form of plant disease control. Finally, B-NBPs are also advantageous in terms of cost and efficiency. They are much less expensive than existing synthetic chemicals and require fewer applications in order to be effective. Furthermore, the targeted nature of these B-NBPs renders them less likely to be ineffective due to environmental conditions or the presence of other competitors.

7. OPPORTUNITIES AND FUTURE PERSPECTIVES

Nanobiopesticides have the option of providing an alternative to chemical-based pesticides that is more effective and safer, but their application is still in its infancy. Thus, there remain restrictions to their deployment that must be addressed. The low efficacy of nanobiopesticides is their primary drawback. They are rapidly washed away during rainfall or irrigation. Thus, they may need to be administered more often than conventional pesticides. A second constraint is that nanobiopesticides are not currently accessible in sufficient quantities for widespread commercial use. This implies that they are only used in a restricted array of industries, and their efficacy is not well-comprehended. The safety consequences of utilizing nanobiopesticides are another restriction. Although they are typically regarded as safer than chemical-based formulations, they may nevertheless cause damage to people and the environment if employed improperly. For instance, if the nanoparticles leveraged in nanobiopesticides are too small, they may be capable of penetrating the skin, posing a danger to human health. Moreover, they might accumulate in the environment and affect wildlife and other ecosystems. There is also the possibility that nanobiopesticides could be utilized inappropriately, leading to a rise in pesticide resistance. This might lead to an increase in the need for pesticides containing chemicals, hence raising the risk of environmental damage. Nevertheless, the application of nanobiopesticides is still relatively new, and research on their long-term environmental consequences is sparse. So, further study is required to comprehend their safety implications.

Regulatory agencies approach the approval procedure for various NBPs and B-NBPs with a positive attitude. However, the use of such B-NBPs demands considerable care and knowledge, especially during field application. In addition, their cost restricts their use in agricultural regions of the so-called third world. Concerning feed and food safety, B-NBPs have the power to revolutionize worldwide agriculture productivity. They present superior efficacy due to their tiny size, vast surface area, durability, improved efficacy, high solubility, adaptability, and minimal toxicity. They might be used in the conception of smart nanosystems to lessen primary agricultural issues such as environmental consequences, food yield, and safety. These B-NBPs and BNPs exhibit superior controlled-release behavior, ensuring their long-term efficacy and capability to counteract eutrophication and pesticide residue buildup. However, the most important barrier to the advancement of such bacterial nanoformulations in agriculture is its ethical acceptability. Farmers are undertrained and uninformed of nanotechnological agricultural facilities on a global scale. The buildup and/or toxicity of nanoparticles in biological systems, such as the food chain, is an additional key issue. Thus, scientists are endeavoring to identify how to adapt to nanoparticle absorption and nonabsorption in a cell or system, which eventually expedites their accumulation. The future study must thus focus on a better knowledge of the characterization, formulation, morphology, and application of NBPs to determine their ultimate fate in animals, people, and plants. Therefore, several elements of NBPs, such as their current state, limitations, prospects, and regulatory framework, must be evaluated regularly to guarantee their effective use for the good of mankind. Further, molecular-level research using diverse animal models should be prioritized in order to adequately depict the mechanism of action involved in pest control. Additionally, the long-term impacts of these NBPs on plants and animals, as well as their stability, and crop-specific application doses, should be examined to ensure agricultural safety and sustainability.

8. CONCLUSIONS

BBCA are attracting attention worldwide as a more effective technique to control pest/phytopathogen populations while posing minimal harm to people and the environment. BBCA coupled with nanotechnology provides efficient ecologically acceptable phytopathogen/pest control choices such as B-NBPs. B-NBPs can be broadly classified into two major categories: the direct-bacterial nanoformulations, which include living or nonliving bacterial nanoforumlations as the first category. For instance, the B-NBP *Bacillus thuringiensis* (Bt), synthesized using microionization techniques with an average size of 250−500 nm, is leveraged to control a wide range of lepidopteran pests, including moths and butterflies. Bacteria-synthesized BNPs belong to the second category B-NBPs. Metabolites from bacteria act as capping and plummeting mediators for the development of nanoparticles. The metal ions are ensnared onto the bacteria and undergo an enzymatic or nonenzymatic process to synthesize MNPs. The prospects are bright for new nanomaterials of bacterial origins referred to as B-NBPs, such as a range of nanoencapsulated bacterial enzymes or harnessing the reducing actions of bacteria for the synthesis of MNPs and/or metal oxide nanoparticles. Given their bacterial origins together with an apparent reduction of chemical toxicity, nanoformulations predicated on bacteria are both cost-effective and environmentally benign. Such B-NBPs are largely accepted by the common masses, as farmers seek them out due to their potency even in small amounts.

Overall, B-NBPS has evolved into a viable plant protection strategy. Plants can withstand insect infestations, diseases, and other external factors more effectively and efficiently when treated with B-NBPS. This strategy not only protects the plants but also benefits the environment by reducing the usage of chemical pesticides. Further, this method is economical and easy to use. With the continual advancement of technology, B-NBPs applications ought to become more extensive. In the future, it will become an important tool in agricultural production and bring more convenience to people's lives. On the whole, B-NBPs are an innovative and focused form of plant protection approach that promises to revolutionize the methods of pests/phytopathogens management and eradication.

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Notes

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REFERENCES

(1) Gámizgámiz, B.; Facenda, G.; Celis, R. Nanoengineered Sorbents To Increase the Persistence of the Allelochemical Carvone in the Rhizosphere. *J. Agric. Food Chem.* **2018**, *67* (2), 589.

(2) Barrón Cuenca, J.; Tirado, N.; Vikström, M.; Lindh, C. H.; Stenius, U.; Leander, K.; Berglund, M.; Dreij, K. Pesticide Exposure among Bolivian Farmers: Associations between Worker Protection and Exposure Biomarkers. *J. Expo Sci. Environ. Epidemiol* **2020**, *30* (4), 730–742.

(3) Ahmaruzzaman, M.; Guidotti, M.; Lapkin, A.; Fraceto, L. F.; Grillo, R.; de Medeiros, G. A.; Scognamiglio, V.; Rea, G.; Bartolucci, C. Nanotechnology in Agriculture: Which Innovation Potential Does It Have? Systems for Sustainable Intensification in Agriculture. *Frontiers in Environmental Science* **2016**, *4*, 20.

(4) Nicolopoulou-Stamati, P.; Maipas, S.; Kotampasi, C.; Stamatis, P.; Hens, L. Chemical Pesticides and Human Health: The Urgent Need for a New Concept in Agriculture. *Front. Public Health* **2016**, *4*, 148.

(5) Kumar, J.; Ramlal, A.; Mallick, D.; Mishra, V. An Overview of Some Biopesticides and Their Importance in Plant Protection for Commercial Acceptance Academic. *Plants (Basel)* **2021**, *10* (6), 1185.

(6) Tabashnik, B. E.; Mota-Sanchez, D.; Whalon, M. E.; Hollingworth, R. M.; Carrière, Y. Defining Terms for Proactive Management of Resistance to Bt Crops and Pesticides. *J. Econ. Entomol.* **2014**, *107* (2), 496–507.

(7) Brevik, K.; Schoville, S. D.; Mota-Sanchez, D.; Chen, Y. H. Pesticide Durability and the Evolution of Resistance: A Novel Application of Survival Analysis. *Pest Manag Sci.* **2018**, *74* (8), 1953–1963.

(8) Ankati, S.; Srinivas, V.; Pratyusha, S.; Gopalakrishnan, S. Streptomyces Consortia-Mediated Plant Defense against Fusarium Wilt and Plant Growth-Promotion in Chickpea. *Microb. Pathog.* **2021**, *157*, 104961.

(9) Gopalakrishnan, S.; Srinivas, V.; Naresh, N.; Pratyusha, S.; Ankati, S.; Madhuprakash, J.; Govindaraj, M.; Sharma, R. Deciphering the Antagonistic Effect of Streptomyces Spp. and Host-Plant Resistance Induction against Charcoal Rot of Sorghum. *Planta* **2021**, *253* (2), 57.

(10) Sathya, A.; Vijayabharathi, R.; Kumari, B. R.; Srinivas, V.; Sharma, H. C.; Sathyadevi, P.; Gopalakrishnan, S. Assessment of a Diketopiperazine, Cyclo(Trp-Phe) from Streptomyces Griseoplanus SAI-25 against Cotton Bollworm, Helicoverpa Armigera (Lepidoptera: Noctuidae). *Appl. Entomol Zool* **2016**, *51* (1), 11–20.

(11) Gopalakrishnan, S.; Rajendran, V.; Arumugam, S.; Sharma, H. C.; Vadlamudi, S.; Bhimineni, R. K.; Gonzalez, S. V.; Melø, T. M.; Simic, N. Insecticidal Activity of a Novel Fatty Acid Amide Derivative from Streptomyces Species against Helicoverpa Armigera. *Nat. Prod. Res.* **2016**, *30* (24), 2760–2769.

(12) Vijayabharathi, R.; Sathya, A.; Gopalakrishnan, S. Extracellular Biosynthesis of Silver Nanoparticles Using Streptomyces Griseoplanus SAI-25 and Its Antifungal Activity against Macrophomina Phaseolina, the Charcoal Rot Pathogen of Sorghum. *Biocatal Agric Biotechnol* **2018**, *14*, 166–171.

(13) Vijayabharathi, R.; Gopalakrishnan, S.; Sathya, A.; Srinivas, V.; Sharma, M. Deciphering the Tri-Dimensional Effect of Endophytic Streptomyces Sp. on Chickpea for Plant Growth Promotion, Helper Effect with Mesorhizobium Ciceri and Host-Plant Resistance Induction against Botrytis Cinerea. *Microb Pathog* **2018**, *122*, 98–107.

(14) Pal, G. K.; Kumar, B.; Nd, A. N.; Kumar Pal, G.; Shahi, S. K. Antifungal Activity of Some Common Weed Extracts Against Seed-Borne Phytopathogenic Fungi Alternaria spp. *International Journal of Universal Pharmacy* **2015**, 3 (2), 6.

(15) Samada, L. H.; Tambunan, U. S. F. Biopesticides as Promising Alternatives to Chemical Pesticides: A Review of Their Current and Future Status. *Online J. Biol. Sci.* **2020**, *20* (2), 66–76.

(16) Seiber, J. N.; Coats, J.; Duke, S. O.; Gross, A. D. Biopesticides: State of the Art and Future Opportunities. *J. Agric. Food Chem.* **2014**, *62*, 11613–11619.

(17) Shah, Z.; Badshah, S. L.; Iqbal, A.; Shah, Z.; Emwas, A. H.; Jaremko, M. Investigation of Important Biochemical Compounds from Selected Freshwater Macroalgae and Their Role in Agriculture. *Chemical and Biological Technologies in Agriculture* **2022**, *9* (1), 9.

(18) Mishra, J.; Arora, N. K. Bioformulations for Plant Growth Promotion and Combating Phytopathogens: A Sustainable Approach. *Bioformulations: For Sustainable Agriculture*; Springer International Publishing, 2016; pp 3–33.

(19) Sun, D.; Zhu, L.; Guo, L.; Wang, S.; Wu, Q.; Crickmore, N.; Zhou, X.; Bravo, A.; Soberón, M.; Guo, Z.; Zhang, Y. A Versatile Contribution of Both Aminopeptidases N and ABC Transporters to Bt Cry1Ac Toxicity in the Diamondback Moth. *BMC Biol.* **2022**, *20* (1), 33 DOI: 10.1186/s12915-022-01226-1.

(20) *Blue Weave Consulting Homepage.* https://www.blueweaveconsulting.com/ (accessed 2023-03-20).

(21) *Global Biological Control Agents Market Size More Than Doubles to Reach USD 11.48 Billion by 2028 |BlueWeave Consulting.* https://www.globenewswire.com/en/news-release/2022/11/10/2553517/0/en/Global-Biological-Control-Agents-Market-Size-More-Than-Doubles-to-Reach-USD-11-48-Billion-by-2028-BlueWeave-Consulting.html (accessed 2023-03-20).

(22) *Biological Biological Control Agents Market - Global Size, Share, Trend Analysis, Opportunity and Forecast Report, 2018–2028, Segmented By Crop (Cereals, Fruits, Vegetables, Pulses, Oilseeds, Others); By Mode of Application (Seed Treatment, Foliar Spray, Soil Treatment, Others); By Target (Arthropods, Weeds, Microorganisms, Others); By Region (North America, Europe, Asia Pacific, Latin America, Middle East and Africa).* https://www.techsciresearch.com/report/biological-control-agents-market/14584.html (accessed 2023-03-20).

(23) *Maximize Market Research Homepage*. https://www.maximizemarketresearch.com/ (accessed 2023-03-20).

(24) Bonaterra, A.; Badosa, E.; Daranas, N.; Francés, J.; Roselló, G.; Montesinos, E. Bacteria as Biological Control Agents of Plant Diseases. *Microorganisms* **2022**, *10*, 1759.

(25) Nuruzzaman, M.; Rahman, M. M.; Liu, Y.; Naidu, R. Nanoencapsulation, Nano-Guard for Pesticides: A New Window for Safe Application. *J. Agric. Food Chem.* **2016**, *64* (7), 1447.

(26) Nuruzzaman, M.; Liu, Y.; Rahman, M. M.; Dharmarajan, R.; Duan, L.; Uddin, A. F. M. J.; Naidu, R. Nanobiopesticides: Composition and Preparation Methods. In *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 69−131.

(27) Manchikanti, P. Bioavailability and Environmental Safety of Nanobiopesticides. *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 207−222.

(28) Joeniarti, E.; Susilo, A.; Ardiarini, N. R.; Indrasari, N.; Fahmi, M. Z. Efficiency Study of Neem Seeds-Based Nanobiopesticides. *Chemistry and Chemical Technology* **2019**, *13* (2), 240−246.

(29) Lade, B. D.; Gogle, D. P.; Lade, D. B.; Moon, G. M.; Nandeshwar, S. B.; Kumbhare, S. D. Nanobiopesticide Formulations: Application Strategies Today and Future Perspectives. *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 179−206.

(30) Deshpande, M. v. Nanobiopesticide Perspectives for Protection and Nutrition of Plants. *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 47−68.

(31) Lade, B. D.; Gogle, D. P.; Lade, D. B.; Moon, G. M.; Nandeshwar, S. B.; Kumbhare, S. D. Nanobiopesticide Formulations: Application Strategies Today and Future Perspectives. *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 179−206.

(32) Kumar, K. K.; Sridhar, J.; Murali-Baskaran, R. K.; Senthil-Nathan, S.; Kaushal, P.; Dara, S. K.; Arthurs, S. Microbial Biopesticides for Insect Pest Management in India: Current Status and Future Prospects. *J. Invertebr Pathol* **2019**, *165*, 74−81.

(33) Ruiu, L. Microbial Biopesticides in Agroecosystems. *Agronomy* **2018**, *8*, 235.

(34) Köhl, J.; Kolnaar, R.; Ravensberg, W. J. Mode of Action of Microbial Biological Control Agents against Plant Diseases: Relevance beyond Efficacy. *Frontiers in Plant Science* **2019**.

(35) Robin, D. C.; Marchand, P. A. Evolution of the Biocontrol Active Substances in the Framework of the European Pesticide Regulation (EC) No. 1107/2009. *Pest Manag Sci.* **2019**, *75* (4), 950−958.

(36) Kumar, P.; Kamle, M.; Borah, R.; Mahato, D. K.; Sharma, B. Bacillus Thuringiensis as Microbial Biopesticide: Uses and Application for Sustainable Agriculture. *Egyptian Journal of Biological Pest Control* **2021**, *31*, 95.

(37) Koul, O. Microbial Biopesticides: Opportunities and Challenges. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **2011**, *6* (56), 1−26.

(38) Bg, A.; Mk, N.; Gopalakrishnan, S.; Ys, A.; Gururaj, S. A Review on the Biological Control of Plant Diseases Using Various Microorganisms. *J. Pharmacogn. Phytochem.* **2019**, *8* (2), 506−510.

(39) Raaijmakers, J. M.; van der Sluis, L.; Koster, M.; Bakker, P. A. H. M.; Weisbeek, P. J.; Schippers, B.; Raaijmakers, I. J. M.; van der Sluis, I.; Bakker, P. A. H. M.; Schippers, B.; Koster, M.; Weisbeek, P. J. Utilization of Heterologous Siderophores and Rhizosphere Competence of Fluorescent Pseudomonas spp. *Canadian Journal of Microbiology* **1995**, *41* (2), 1.

(40) Raaijmakers, J. M.; Mazzola, M. Diversity and Natural Functions of Antibiotics Produced by Beneficial and Plant Pathogenic Bacteria. *Annual Review of Phytopathology* **2012**, *50*, 403−424.

(41) Kalia, V. C.; Patel, S. K. S.; Kang, Y. C.; Lee, J.-K. Quorum Sensing Inhibitors as Antipathogens: Biotechnological Applications. *Biotechnol Adv.* **2019**, *37* (1), 68−90.

(42) Spadaro, D.; Droby, S. Development of Biocontrol Products for Postharvest Diseases of Fruit: The Importance of Elucidating the Mechanisms of Action of Yeast Antagonists. *Trends in Food Science and Technology* **2016**, *47*, 39−49.

(43) Ghorbanpour, M.; Omidvari, M.; Abbaszadeh-Dahaji, P.; Omidvar, R.; Kariman, K. Mechanisms Underlying the Protective Effects of Beneficial Fungi against Plant Diseases. *Biological Control* **2018**, *117*, 147−157.

(44) Pieterse, C. M. J.; Zamioudis, C.; Berendsen, R. L.; Weller, D. M.; van Wees, S. C. M.; Bakker, P. A. H. M. Induced Systemic Resistance by Beneficial Microbes. *Annu. Rev. Phytopathol* **2014**, *52*, 347−375.

(45) Conrath, U.; Beckers, G. J. M.; Langenbach, C. J. G.; Jaskiewicz, M. R. Priming for Enhanced Defense. *Annual Review of Phytopathology* **2015**, *53*, 97−119.

(46) Jampilek, J.; Kralova, K. Nanobiopesticides in Agriculture: State of the Art and Future Opportunities. *Nano-biopesticides today and future perspectives; Elsevier* **2019**, 397−447.

(47) Zhang, J.; Brown, G.; Fu, J.; James, P.; Mukandiwa, L.; Huang, X.; Yu, C. Nanobiopesticides: Silica Nanoparticles with Spiky Surfaces Enable Dual Adhesion and Enhanced Performance. *EcoMat* **2020**, *2* (2), No. e12028.

(48) Damalas, C. A.; Koutroubas, S. D. Current Status and Recent Developments in Biopesticide Use. *Agriculture (Switzerland)* **2018**, *8* (1), 13.

(49) Hubbard, M.; Hynes, R. K.; Erlandson, M.; Bailey, K. L. The Biochemistry behind Biopesticide Efficacy. *Sustainable Chemical Processes* **2014**, *2* (1), 18.

(50) Kumar, S.; Singh, A. Biopesticides: Present Status and the Future Prospects. *Journal of Fertilizers & Pesticides* **2015**, *6* (2), e129.

(51) Mishra, J.; Dutta, V.; Arora, N. K. Biopesticides in India: Technology and Sustainability Linkages. *3 Biotech* **2020**, *10* (5), 210.

(52) Shang, Y.; Hasan, Md. K.; Ahammed, G. J.; Li, M.; Yin, H.; Zhou, J. Applications of Nanotechnology in Plant Growth and Crop Protection: A Review. *Molecules* **2019**, *24* (14), 2558.

(53) Sekhon, B. Nanotechnology in Agri-Food Production: An Overview. *Nanotechnol Sci. Appl.* **2014**, *7*, 31−53.

(54) Deka, B.; Babu, A.; Baruah, C.; Barthakur, M. Nanopesticides: A Systematic Review of Their Prospects With Special Reference to Tea Pest Management. *Frontiers in Nutrition* **2021**.

(55) Hazafa, A.; Jahan, N.; Zia, M. A.; Rahman, K. U.; Sagheer, M.; Naeem, M. Evaluation and Optimization of Nanosuspensions of Chrysanthemum Coronarium and Azadirachta Indica Using Response Surface Methodology for Pest Management. *Chemosphere* **2022**, *292*, 133411.

(56) de Castro e Silva, P.; Pereira, L. A. S.; Lago, A. M. T.; Valquiria, M.; de Rezende, E. M.; Carvalho, G. R.; Oliveira, J. E.; Marconcini, J. M. Physical-Mechanical and Antifungal Properties of Pectin Nanocomposites/Neem Oil Nanoemulsion for Seed Coating. *Food Biophys.* **2019**, *14* (4), 456−466.

(57) Kumar, S.; Nehra, M.; Dilbaghi, N.; Marrazza, G.; Hassan, A. A.; Kim, K. H. Nano-Based Smart Pesticide Formulations: Emerging Opportunities for Agriculture. *J. Controlled Release* **2019**, *294*, 131−153.

(58) Candido Camara, M.; Aparecida Monteiro, R.; Braganc, L.; Luiz Oliveira, J.; Fraceto, L. F. Enzyme Stimuli−Responsive Nanoparticles for Bioinsecticides: An Emerging Approach for Uses in Crop Protection. *ACS Sustainable Chem. Eng.* **2020**, *9* (1), 106−112.

(59) Ahmed, T.; Wu, Z.; Jiang, H.; Luo, J.; Noman, M.; Shahid, M.; Manzoor, I.; Allemailem, K. S.; Alrumaihi, F.; Li, B.; Mortimer, M.; Kahru, A. Bioinspired Green Synthesis of Zinc Oxide Nanoparticles from a Native Bacillus Cereus Strain RNT6: Characterization and Antibacterial Activity against Rice Panicle Blight Pathogens Burkholderia glumae and B. gladioli. *Nanomaterials* **2021**, *11* (4), 884.

(60) Oliveira, C. R.; Domingues, C. E. C.; de Melo, N. F. S.; Roat, T. C.; Malaspina, O.; Jones-Costa, M.; Silva-Zacarin, E. C. M.; Fraceto, L. F. Nanopesticide Based on Botanical Insecticide Pyrethrum and Its Potential Effects on Honeybees. *Chemosphere* **2019**, *236*, 124282.

(61) Lu, Z.; Zhang, C.; Gao, Y.; Wang, W.; Lin, J.; Du, F. Simple, Effective, and Energy-Efficient Strategy to Construct a Stable Pesticide Nanodispersion. *ACS Agric. Sci. Technol.* **2021**, *1* (4), 329−337.

(62) Takeshita, V.; de Sousa, B. T.; Preisler, A. C.; Carvalho, L. B.; Pereira, A. do E. S.; Tornisielo, V. L.; Dalazen, G.; Oliveira, H. C.; Fraceto, L. F. Foliar Absorption and Field Herbicidal Studies of Atrazine-Loaded Polymeric Nanoparticles. *J. Hazard Mater.* **2021**, *418*, 126350.

(63) Wang, P.; Galhardi, J. A.; Liu, L.; Bueno, V.; Ghoshal, S.; Gravel, V.; Wilkinson, K. J.; Bayen, S. Development of an LC-MS-Based Method to Study the Fate of Nanoencapsulated Pesticides in Soils and Strawberry Plant. *Talanta* **2022**, *239*, 123093.

(64) Nyyssölä, A.; Ojala, L. S.; Wuokko, M.; Peddinti, G.; Tamminen, A.; Tsitko, I.; Nordlund, E.; Lienemann, M. Production of Endotoxin-Free Microbial Biomass for Food Applications by Gas Fermentation of Gram-Positive H 2 -Oxidizing Bacteria. *ACS Food Science & Technology* **2021**, *1* (3), 470−479.

(65) Levin, P. A.; Angert, E. R. Small but Mighty: Cell Size and Bacteria. *Cold Spring Harb. Perspect. Biol.* **2015**, *7* (7), a019216.

(66) Roh, J. Y.; Choi, J. Y.; Li, M. S.; Jin, B. R.; Je, Y. H. Bacillus thuringiensis as a Specific, Safe, and Effective Tool for Insect Pest. *J. Microbiol. Biotechnol.* **2007**, *17* (4), 547.

(67) Shatalova, E. I.; Grizanova, E. v.; Dubovskiy, I. M. The Effect of Silicon Dioxide Nanoparticles Combined with Entomopathogenic Bacteria or Fungus on the Survival of Colorado Potato Beetle and Cabbage Beetles. *Nanomaterials* **2022**, *12* (9), 1558.

(68) Panagou, Z.; Chen, M.; Wei, X.; Zhang, J.; Zhou, H.; Chen, N.; Wang, J.; Feng, Y.; Yu, S.; Zhang, J.; Wu, S.; Ye, Q.; Pang, R.; Ding, Y.; Wu, Q. Microorganisms Differentiation of Bacillus Cereus and Bacillus Thuringiensis Using Genome-Guided MALDI-TOF MS Based on Variations in Ribosomal Proteins. *Microorganisms* **2022**, *10* (5), 918.

(69) Khan, M.; Salman, M.; Shah, S. H.; Israr, M. In Vitro Antifungal Potential of Surfactin Isolated from Rhizospheric Bacillus Thuringiensis Berliner 1915 against Maize (Zea Mays L.) Fungal Phytopathogen Fusarium Graminearum Schwabe. *Acta Agric. Slov.* **2021**, *117* (4), 1.

(70) Navya, R. N. S.; Balasubramani, V.; Raveendran, M.; Murugan, M.; Lakshmanan, A. Characterization of Indigenous Bacillus Thuringiensis Isolate RM11 Toxic to the Diamondback Moth, Plutella Xylostella (L.) (Lepidoptera: Plutellidae). *Egypt J. Biol. Pest Control* **2022**, *32* (1), 56.

(71) Patel, R.; Piper, K.; Cockerill, F. R.; Steckelberg, J. M.; Yousten, A. A. The Biopesticide Paenibacillus Popilliae Has a Vancomycin Resistance Gene Cluster Homologous to the Enterococcal VanA Vancomycin Resistance Gene Cluster. *Antimicrob. Agents Chemother.* **2000**, *44* (3), 705.

(72) Ibrahim, M. A.; Griko, N.; Junker, M.; Bulla, L. A. Bacillus Thuringiensis A Genomics and Proteomics Perspective Background and History. *Bioeng Bugs* **2010**, *1* (1), 31−50.

(73) Iqrar, I.; Numan, M.; Khan, T.; Shinwari, Z. K.; Ali, G. S. LC-MS/MS-Based Profiling of Bioactive Metabolites of Endophytic Bacteria from Cannabis Sativa and Their Anti-Phytophthora Activity. *Antonie van Leeuwenhoek* **2021**, *114* (8), 1165.

(74) Konecka, E.; Mokracka, J.; Krzyminska, S.; Kaznowski, A. Evaluation of the Pathogenic Potential of Insecticidal Serratia Marcescens Strains to Humans. *Pol J. Microbiol* **2019**, *68* (2), 185−191.

(75) Kupferschmied, P.; Maurhofer, M.; Keel, C.; Reymond, P.; Nielsen-LeRoux, C. Promise for Plant Pest Control: Root-Associated Pseudomonads with Insecticidal Activities. *Front. Plant Sci.* **2013**, *4*, 287.

(76) Flury, P.; Aellen, N.; Ruffner, B.; Péchy-Tarr, M.; Fataar, S.; Metla, Z.; Dominguez-Ferreras, A.; Bloemberg, G.; Frey, J.; Goesmann, A.; Raaijmakers, J. M.; Duffy, B.; Höfte, M.; Blom, J.; Smits, T. H. M.; Keel, C.; Maurhofer, M. Insect Pathogenicity in Plant-Beneficial Pseudomonads: Phylogenetic Distribution and Comparative Genomics. *ISME Journal* **2016**, *10* (10), 2527−2542.

(77) Chopra, A.; Bobate, S.; Rahi, P.; Banpurkar, A.; Mazumder, P. B.; Satpute, S. Pseudomonas Aeruginosa RTE4: A Tea Rhizobacterium With Potential for Plant Growth Promotion and Biosurfactant Production. *Front. Bioeng. Biotechnol.* **2020**, *8*, 861.

(78) Salazar, B.; Ortiz, A.; Keswani, C.; Minkina, T.; Mandzhieva, S.; Pratap Singh, S.; Rekadwad, B.; Borriss, R.; Jain, A.; Singh, H. B.; Sansinenea, E. Bacillus Spp. as Bio-Factories for Antifungal Secondary Metabolites: Innovation Beyond Whole Organism Formulations. *Microb. Ecol.* **2022**.

(79) Kumar, P.; Pandhi, S.; Mahato, D. K.; Kamle, M.; Mishra, A. Bacillus-Based Nano-Bioformulations for Phytopathogens and Insect−Pest Management. *Egyptian Journal of Biological Pest Control* **2021**, *31*, 128.

(80) Arrebola, E.; Jacobs, R.; Korsten, L. Iturin A Is the Principal Inhibitor in the Biocontrol Activity of Bacillus Amyloliquefaciens PPCB004 against Postharvest Fungal Pathogens. *J. Appl. Microbiol.* **2010**, *108* (2), 386−395.

(81) Waewthongrak, W.; Pisuchpen, S.; Leelasuphakul, W. Effect of Bacillus Subtilis and Chitosan Applications on Green Mold (Penicilium Digitatum Sacc.) Decay in Citrus Fruit. *Postharvest Biol. Technol.* **2015**, *99*, 44−49.

(82) Choe, S. G.; Maeng, H. R.; Pak, S. J.; U, S. N. Production of Bacillus Thuringiensis Biopesticide Using Penicillin Fermentation Waste Matter and Application in Agriculture. *Journal of Natural Pesticide Research* **2022**, *2*, 100012.

(83) Ma, Z.; Wang, N.; Hu, J.; Wang, S. Isolation and Characterization of a New Iturinic Lipopeptide, Mojavensin A Produced by a Marine-Derived Bacterium Bacillus Mojavensis B0621A. *J. Antibiot.* **2012**, *65* (6), 317−322.

(84) Pereira De Melo, F. M.; Fiore, M. F.; Beraldo De Moraes, L. A.; Silva-Stenico, M. E.; Scramin, S.; Teixeira, M. d. A.; Soares De Melo, I. Antifungal compound produced by the cassava endophyte Bacillus pumilus MAIIIM4a. *Scientia Agricola* **2009**, *66* (5), 583.

(85) Koppenhöfer, A. M.; Jackson, T. A.; Klein, M. G. Chapter V - Bacteria for Use against Soil-Inhabiting Insects. In *Manual of Techniques in Invertebrate Pathology*, second ed.; Lacey, L. A., Ed.; Academic Press: San Diego, CA, 2012; pp 129−149.

(86) Daranas, N.; Roselló, G.; Cabrefiga, J.; Donati, I.; Francés, J.; Badosa, E.; Spinelli, F.; Montesinos, E.; Bonaterra, A. Biological Control of Bacterial Plant Diseases with Lactobacillus Plantarum Strains Selected for Their Broad-Spectrum Activity. *Annals of Applied Biology* **2019**, *174* (1), 92−105.

(87) Díaz-Díaz, M.; Bernal-Cabrera, A.; Trapero, A.; Medina-Marrero, R.; Sifontes-Rodríguez, S.; Cupull-Santana, R. D.; García-Bernal, M.; Agustí-Brisach, C. Characterization of Actinobacterial Strains as Potential Biocontrol Agents against Macrophomina Phaseolina and Rhizoctonia Solani, the Main Soil-Borne Pathogens of Phaseolus Vulgaris in Cuba. *Plants* **2022**, *11* (5), 645.

(88) Wang, M.; Xue, J.; Ma, J.; Feng, X.; Ying, H.; Xu, H. Streptomyces Lydicus M01 Regulates Soil Microbial Community and Alleviates Foliar Disease Caused by Alternaria Alternata on Cucumbers. *Front. Microbiol.* **2020**, *11*, 942.

(89) Calderón, C. E.; Pérez-García, A.; de Vicente, A.; Cazorla, F. M. The Dar Genes of Pseudomonas Chlororaphis PCL1606 Are Crucial for Biocontrol Activity via Production of the Antifungal Compound 2-Hexyl, 5-Propyl Resorcinol. *Mol. Plant-Microbe Interact.* **2013**, *26* (5), 554−565.

(90) Montes-Osuna, N.; Cabanás, C. G. L.; Valverde-Corredor, A.; Berendsen, R. L.; Prieto, P.; Mercado-Blanco, J. Assessing the Involvement of Selected Phenotypes of Pseudomonas Simiae PICF7 in Olive Root Colonization and Biological Control of Verticillium Dahliae. *Plants* **2021**, *10* (2), 412.

(91) Trias, R.; Badosa, E.; Montesinos, E.; Bañeras, L. Bioprotective Leuconostoc Strains against Listeria Monocytogenes in Fresh Fruits and Vegetables. *Int. J. Food Microbiol.* **2008**, *127* (1−2), 91−98.

(92) Kumari, B.; Mallick, M. A.; Solanki, M. K.; Hora, A.; Mani, M. Applying Nanotechnology to Bacteria: An Emerging Technology for Sustainable Agriculture. *Role of Plant Growth Promoting Microorganisms in Sustainable Agriculture and Nanotechnology*; Elsevier, 2019; pp 121−143.

(93) Poopathi, S.; Abidha, S. Mosquitocidal Bacterial Toxins (Bacillus Sphaericus and Bacillus Thuringiensis Serovar Israelensis): Mode of Action, Cytopathological Effects and Mechanism of Resistance. *Global Journal of Anatomy and Physiology* **2013**, *1*, 53−69.

(94) Kachhawa, D. Microorganisms as a Biopesticides. *Journal of Entomology and Zoology Studies* **2017**, *5* (3), 468−473.

(95) Yadav, D. R.; Adhikari, M.; Kim, S. W.; Kim, H. S.; Lee, Y. S. Suppression of Fusarium Wilt Caused by Fusarium Oxysporum f. Sp. Lactucae and Growth Promotion on Lettuce Using Bacterial Isolates. *J. Microbiol Biotechnol* **2021**, *31* (9), 1241−1255.

(96) Félix-Pablos, C. M.; Parra-Cota, F. I.; Santoyo, G.; Orozco-Mosqueda, M. d. C.; de los Santos-Villalobos, S. Draft Genome Sequence of Bacillus Sp. Strain FSQ1, a Biological Control Agent against White Mold in Common Bean (Phaseolus Vulgaris L.). *Curr. Res. Microb Sci.* **2022**, *3*, 100138.

(97) de Oliveira, J. L.; Fraceto, L. F.; Bravo, A.; Polanczyk, R. A. Encapsulation Strategies for Bacillus Thuringiensis: From Now to the Future. *J. Agric. Food Chem.* **2021**, *69* (16), 4564−4577.

(98) Guo, L.; Cheng, Z.; Qin, J.; Sun, D.; Wang, S.; Wu, Q.; Crickmore, N.; Zhou, X.; Bravo, A.; Soberón, M.; Guo, Z.; Zhang, Y. MAPK-Mediated Transcription Factor GATAd Contributes to Cry1Ac Resistance in Diamondback Moth by Reducing PxmALP Expression. *PLoS Genet.* **2022**, *18*, e1010037.

(99) Yaakov, N.; Kottakota, C.; Mani, K. A.; Naftali, S. M.; Zelinger, E.; Davidovitz, M.; Ment, D.; Mechrez, G. Encapsulation of Bacillus Thuringiensis in an Inverse Pickering Emulsion for Pest Control Applications. *Colloids Surf. B Biointerfaces* **2022**, *213*, 112427.

(100) Naureen, Z.; Rehman, N. U.; Hussain, H.; Hussain, J.; Gilani, S. A.; Al Housni, S. K.; Mabood, F.; Khan, A. L.; Farooq, S.; Abbas, G.; Harrasi, A. A. Exploring the Potentials of Lysinibacillus Sphaericus ZA9 for Plant Growth Promotion and Biocontrol Activities against Phytopathogenic Fungi. *Front. Microbiol.* **2017**, *8* (AUG), 1477.

(101) Abd-El-Kareem, F.; Elshahawy, I. E.; Abd-Elgawad, M. M. M. Application of Bacillus Pumilus Isolates for Management of Black Rot Disease in Strawberry. *Egypt J. Biol. Pest Control* **2021**, *31* (1), 25.

(102) Barbieri, G.; Ferrari, C.; Mamberti, S.; Gabrieli, P.; Castelli, M.; Sassera, D.; Ursino, E.; Scoffone, V. C.; Radaelli, G.; Clementi, E.; Sacchi, L.; Ferrari, E.; Gasperi, G.; Albertini, A. M. Identification of a Novel Brevibacillus Laterosporus Strain With Insecticidal Activity Against Aedes Albopictus Larvae. *Front. Microbiol.* **2021**, *12*, 624014.

(103) George, Z.; Crickmore, N. Bacillus Thuringiensis Applications in Agriculture. *Bacillus thuringiensis Biotechnology*; Springer Netherlands, 2013; pp 19−39.

(104) Sanchis, V.; Bourguet, D. Bacillus Thuringiensis: Applications in Agriculture and Insect Resistance Management. A Review. *Agron. Sustainable Dev.* **2008**, *28*, 11−20.

(105) Devi, P. S. V.; Duraimurugan, P.; Chandrika, K. S. V. P. Bacillus Thuringiensis-Based Nanopesticides for Crop Protection. *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 249−260.

(106) Schisler, D. A.; Slininger, P. J.; Behle, R. W.; Jackson, M. A. Formulation of Bacillus spp. for Biological Control of Plant Diseases. *Phytopathology* **2004**, *94* (11), 1267.

(107) Medina-Pérez, G.; Fernández-Luqueño, F.; Campos-Montiel, R. G.; Sánchez-López, K. B.; Afanador-Barajas, L. N.; Prince, L. Nanotechnology in Crop Protection: Status and Future Trends. *Nano-Biopesticides Today and Future Perspectives*; Elsevier, 2019; pp 17−45.

(108) Burges, H. D.; Hall, R. A. Bacteria and Fungi as Insecticides. *Outlook Agric.* **1982**, *11* (2), 79.

(109) Khadka, P.; Ro, J.; Kim, H.; Kim, I.; Kim, J. T.; Kim, H.; Cho, J. M.; Yun, G.; Lee, J. Pharmaceutical Particle Technologies: An Approach to Improve Drug Solubility, Dissolution and Bioavailability. *Asian Journal of Pharmaceutical Sciences* **2014**, *9* (6), 304−316.

(110) Chingunpituk, J. Nanosuspension Technology for Drug Delivery. *Walailak J. Sci. & Tech.* **2007**, *4* (2), 139.

(111) Vineela, V.; Nataraj, T.; Reddy, G.; Vimala Devi, P. S. Enhanced Bioefficacy of Bacillus Thuringiensis Var. Kurstaki against Spodoptera Litura (Lepidoptera: Noctuidae) through Particle Size Reduction and Formulation as a Suspension Concentrate. *Biocontrol Sci. Technol.* **2017**, *27* (1), 58−69.

(112) Kim, J. S.; Je, Y. H. Milling Effect on the Control Efficacy of Spray-Dried Bacillus Thuringiensis Technical Powder against Diamondback Moths. *Pest Manag Sci.* **2012**, *68* (3), 321−323.

(113) Santha Murthy, K.; Vineela, V.; Vimala Devi, P. Generation of Nanoparticles from Technical Powder of the Insecticidal Bacterium Bacillus Thuringiensis Var. Kurstaki for Improving Efficacy. *International Journal of Biomedical Nanoscience and Nanotechnology* **2014**, *3* (3), 236.

(114) Meruvu, H.; Vangalapati, M.; Chippada, S. C.; Rao Bammidi, S. Synthesis and Characterization Of Zinc Oxide Nanoparticles and Its Antimicrobial Activity Against Bacillus subtilisa and Escherichia coli. *Rasayan J. Chem.* **2011**, *4* (1), 217−222.

(115) Mm, S.; Sm, S. Observations of the Effect of Two Isolated Nano Bacillus Thuringiensis on Tuta Absoluta Infestation under Laboratory and Field Condition. *Res. J. Pharm., Biol. Chem. Sci.* **2016**, *7* (2), 1891.

(116) Glare, T.; Caradus, J.; Gelernter, W.; Jackson, T.; Keyhani, N.; Köhl, J.; Marrone, P.; Morin, L.; Stewart, A. Have Biopesticides Come of Age? *Trends Biotechnol.* **2012**, *30* (5), 250−258.

(117) Ghormade, V.; Deshpande, M. v.; Paknikar, K. M. Perspectives for Nano-Biotechnology Enabled Protection and Nutrition of Plants. *Biotechnology Advances* **2011**, *29* (6), 792−803.

(118) Maghsoudi, S.; Jalali, E. Noble UV Protective Agent for Bacillus Thuringiensis Based on a Combination of Graphene Oxide and Olive Oil. *Sci. Rep.* **2017**, *7* (1), 11019.

(119) Malaikozhundan, B.; Vaseeharan, B.; Vijayakumar, S.; Thangaraj, M. P. Bacillus Thuringiensis Coated Zinc Oxide Nanoparticle and Its Biopesticidal Effects on the Pulse Beetle, Callosobruchus Maculatus. *J. Photochem. Photobiol. B* **2017**, *174*, 306−314.

(120) Qin, X.; Xiang, X.; Sun, X.; Ni, H.; Li, L. Preparation of Nanoscale Bacillus Thuringiensis Chitinases Using Silica Nanoparticles for Nematicide Delivery. *Int. J. Biol. Macromol.* **2016**, *82*, 13−21.

(121) Tamez-Guerra, P.; Mcguire, M. R.; Behle, R. W.; Shasha, B. S.; Galangal, L. J.; Wong, G. Assessment of Microencapsulated Formulations for Improved Residual Activity of Bacillus Thuringiensis. *J. Econ. Entomol.* **2000**, *93*, 219.

(122) Lan, L.; Jin-Can, C.; Zhao-Yuan, Y.; Dong-Zhe, L.; Wei, W.; Wen-Hua, R.; Xiao-Hong, P.; Xiong, G. The Effect of Nano-Mg(OH) 2 on Insecticidal Activity and UV Resistance of Bacillus Thuringiensis Protein. *Journal of Agricultural Biotechnology* **2013**, *23* (11), 1452−1457.

(123) Ghiuţă, I.; Cristea, D.; Croitoru, C.; Kost, J.; Wenkert, R.; Vyrides, I.; Anayiotos, A.; Munteanu, D. Characterization and Antimicrobial Activity of Silver Nanoparticles, Biosynthesized Using Bacillus Species. *Appl. Surf. Sci.* **2018**, *438*, 66−73.

(124) Koul, B.; Poonia, A. K.; Yadav, D.; Jin, J. O. Microbe-Mediated Biosynthesis of Nanoparticles: Applications and Future Prospects. *Biomolecules* **2021**, *11* (6), 886.

(125) Bahrulolum, H.; Nooraei, S.; Javanshir, N.; Tarrahimofrad, H.; Mirbagheri, V. S.; Easton, A. J.; Ahmadian, G. Green Synthesis of Metal Nanoparticles Using Microorganisms and Their Application in the Agrifood Sector. *J. Nanobiotechnol.* **2021**.

(126) Jeevanandam, J.; Kiew, S. F.; Boakye-Ansah, S.; Lau, S. Y.; Barhoum, A.; Danquah, M. K.; Rodrigues, J. Green Approaches for the Synthesis of Metal and Metal Oxide Nanoparticles Using Microbial and Plant Extracts. *Nanoscale* **2022**, *14* (7), 2534−2571.

(127) Senthil-Nathan, S. A Review of Biopesticides and Their Mode of Action against Insect Pests. *Environmental Sustainability: Role of Green Technologies*; Springer, 2015; pp 49−64.

(128) Bahrulolum, H.; Nooraei, S.; Javanshir, N.; Tarrahimofrad, H.; Mirbagheri, V. S.; Easton, A. J.; Ahmadian, G. Green Synthesis of Metal Nanoparticles Using Microorganisms and Their Application in the Agrifood Sector. *J. Nanobiotechnol.* **2021**.

(129) Ali, M. A.; Ahmed, T.; Wu, W.; Hossain, A.; Hafeez, R.; Islam Masum, M. M.; Wang, Y.; An, Q.; Sun, G.; Li, B. Advancements in Plant and Microbe-Based Synthesis of Metallic Nanoparticles and Their Antimicrobial Activity against Plant Pathogens. *Nanomaterials* **2020**, *10* (6), 1146.

(130) Gopinath, V.; Velusamy, P. Extracellular Biosynthesis of Silver Nanoparticles Using Bacillus Sp. GP-23 and Evaluation of Their Antifungal Activity towards Fusarium Oxysporum. *Spectrochim Acta A Mol. Biomol Spectrosc* **2013**, *106*, 170−174.

(131) Ajaz, S.; Ahmed, T.; Shahid, M.; Noman, M.; Shah, A. A.; Mehmood, M. A.; Abbas, A.; Cheema, A. I.; Iqbal, M. Z.; Li, B. Bioinspired Green Synthesis of Silver Nanoparticles by Using a Native Bacillus Sp. Strain AW1−2: Characterization and Antifungal Activity against Colletotrichum Falcatum Went. *Enzyme Microb. Technol.* **2021**, *144*, 109745.

(132) Lin, N.; Wang, C.; Ding, J.; Su, L.; Xu, L.; Zhang, B.; Zhang, Y.; Fan, J. Efficacy of Nanoparticle Encapsulation on Suppressing

Oxidation and Enhancing Antifungal Activity of Cyclic Lipopeptides Produced by Bacillus Subtilis. *Colloids Surf. B Biointerfaces* **2020**, *193*, 111143.

(133) Hassan, S. E.-D.; Salem, S. S.; Fouda, A.; Awad, M. A.; El-Gamal, M. S.; Abdo, A. M. New Approach for Antimicrobial Activity and Bio-Control of Various Pathogens by Biosynthesized Copper Nanoparticles Using Endophytic Actinomycetes. *J. Radiat Res. Appl. Sci.* **2018**, *11* (3), 262−270.

(134) Ponmurugan, P.; Manjukarunambika, K.; Elango, V.; Gnanamangai, B. M. Antifungal Activity of Biosynthesised Copper Nanoparticles Evaluated against Red Root-Rot Disease in Tea Plants. *J. Exp Nanosci* **2016**, *11* (13), 1019−1031.

(135) Karmakar, S.; Ghosh, S.; Kumbhakar, P. Enhanced Sunlight-Driven Photocatalytic and Antibacterial Activities of Flower-Like ZnO@MoS$_2$ Nanocomposite. *J. Nanopart. Res.* **2020**, *22* (1), 11.

(136) Jayaseelan, C.; Rahuman, A. A.; Kirthi, A. V.; Marimuthu, S.; Santhoshkumar, T.; Bagavan, A.; Gaurav, K.; Karthik, L.; Rao, K. V. B. Novel Microbial Route to Synthesize ZnO Nanoparticles Using Aeromonas Hydrophila and Their Activity against Pathogenic Bacteria and Fungi. *Spectrochim Acta A Mol. Biomol Spectrosc* **2012**, *90*, 78−84.

(137) KLICH, M. A. Aspergillus Flavus: The Major Producer of Aflatoxin. *Mol. Plant Pathol* **2007**, *8* (6), 713−722.

(138) Ghosh, S.; Ahmad, R.; Banerjee, K.; AlAjmi, M. F.; Rahman, S. Mechanistic Aspects of Microbe-Mediated Nanoparticle Synthesis. *Frontiers in Microbiology* **2021**.

(139) Lahiri, D.; Nag, M.; Sheikh, H. I.; Sarkar, T.; Edinur, H. A.; Pati, S.; Ray, R. R. Microbiologically-Synthesized Nanoparticles and Their Role in Silencing the Biofilm Signaling Cascade. *Frontiers in Microbiology* **2021**.

(140) Li, J.; Li, Q.; Ma, X.; Tian, B.; Li, T.; Yu, J.; Dai, S.; Weng, Y.; Hua, Y. Biosynthesis of Gold Nanoparticles by the Extreme Bacterium < em > Deinococcus Radiodurans</Em> and an Evaluation of Their Antibacterial Properties. *Int. J. Nanomedicine* **2016**, *11*, 5931−5944.

(141) Ibrahim, E.; Fouad, H.; Zhang, M.; Zhang, Y.; Qiu, W.; Yan, C.; Li, B.; Mo, J.; Chen, J. Biosynthesis of Silver Nanoparticles Using Endophytic Bacteria and Their Role in Inhibition of Rice Pathogenic Bacteria and Plant Growth Promotion. *RSC Adv.* **2019**, *9* (50), 29293−29299.

(142) Journal, A. I.; Fouad, H.; Li, H.; Yanmei, D.; Baoting, Y.; El-Shakh, A.; Abbas, G.; Jianchu, M.; Hongjie, L. Synthesis and characterization of silver nanoparticles using Bacillus amyloliquefaciens and Bacillus subtilis to control filarial vector Culex pipiens pallens and its antimicrobial activity. *Artif. Cells, Nanomed., Biotechnol.* **2016**, *45* (7), 1369.

(143) Tariq, R.; Ji, Z.; Wang, C.; Tang, Y.; Zou, L.; Sun, H.; Chen, G.; Zhao, K. RNA-Seq Analysis of Gene Expression Changes Triggered by Xanthomonas Oryzae Pv. Oryzae in a Susceptible Rice Genotype. *Rice* **2019**, *12* (1), 44.

(144) Kanmani, P.; Lim, S. T. Synthesis and Structural Characterization of Silver Nanoparticles Using Bacterial Exopolysaccharide and Its Antimicrobial Activity against Food and Multidrug Resistant Pathogens. *Process Biochemistry* **2013**, *48* (7), 1099−1106.

(145) Kouhkan, M.; Ahangar, P.; Babaganjeh, L. A.; Allahyari-Devin, M. Biosynthesis of Copper Oxide Nanoparticles Using Lactobacillus Casei Subsp. Casei and Its Anticancer and Antibacterial Activities. *Curr. Nanosci* **2020**, *16* (1), 101−111.

(146) Law, N.; Ansari, S.; Livens, F. R.; Renshaw, J. C.; Lloyd, J. R. Formation of Nanoscale Elemental Silver Particles via Enzymatic Reduction by *Geobacter Sulfurreducens*. *Appl. Environ. Microbiol.* **2008**, *74* (22), 7090−7093.

(147) Ibrahim, E.; Zhang, M.; Zhang, Y.; Hossain, A.; Qiu, W.; Chen, Y.; Wang, Y.; Wu, W.; Sun, G.; Li, B. Green-Synthesization of Silver Nanoparticles Using Endophytic Bacteria Isolated from Garlic and Its Antifungal Activity against Wheat Fusarium Head Blight Pathogen Fusarium Graminearum. *Nanomaterials* **2020**, *10* (2), 219.

(148) Ponmurugan, P.; Manjukarunambika, K.; Elango, V.; Gnanamangai, B. M. Antifungal Activity of Biosynthesised Copper Nanoparticles Evaluated against Red Root-Rot Disease in Tea Plants. *J. Exp Nanosci* **2016**, *11* (13), 1019−1031.

(149) Fouda, A.; Hassan, S. E. D.; Abdo, A. M.; El-Gamal, M. S. Antimicrobial, Antioxidant and Larvicidal Activities of Spherical Silver Nanoparticles Synthesized by Endophytic Streptomyces Spp. *Biol. Trace Elem Res.* **2020**, *195* (2), 707−724.

(150) Mishra, S.; Singh, B. R.; Naqvi, A. H.; Singh, H. B. Potential of Biosynthesized Silver Nanoparticles Using Stenotrophomonas Sp. BHU-S7 (MTCC 5978) for Management of Soil-Borne and Foliar Phytopathogens. *Sci. Rep* **2017**, *7* (1), 45154.

(151) Hossain, A.; Hong, X.; Ibrahim, E.; Li, B.; Sun, G.; Meng, Y.; Wang, Y.; An, Q. Green Synthesis of Silver Nanoparticles with Culture Supernatant of a Bacterium Pseudomonas Rhodesiae and Their Antibacterial Activity against Soft Rot Pathogen Dickeya Dadantii. *Molecules* **2019**, *24* (12), 2303.

(152) Abdel-Aziz, S. M.; Prasad, R.; Hamed, A. A.; Abdelraof, M. Fungal Nanoparticles: A Novel Tool for a Green Biotechnology? *Fungal Nanobionics: Principles and Applications*; Springer Singapore: Singapore, 2018; pp 61−87.

(153) Venil, C. K.; Usha, R.; Devi, P. R. Green Synthesis of Nanoparticles from Microbes and Their Prospective Applications. *Nanomaterials Application in Biofuels and Bioenergy Production Systems*; Elsevier, 2021; pp 283−298.

(154) Ovais, M.; Khalil, A.; Ayaz, M.; Ahmad, I.; Nethi, S.; Mukherjee, S. Biosynthesis of Metal Nanoparticles via Microbial Enzymes: A Mechanistic Approach. *Int. J. Mol. Sci.* **2018**, *19* (12), 4100.

(155) Pantidos, N. Biological Synthesis of Metallic Nanoparticles by Bacteria, Fungi and Plants. *J. Nanomed. Nanotechnol.* **2014**, *5* (5), 1000233.

(156) Koli, S. H.; Mohite, B. v.; Suryawanshi, R. K.; Borase, H. P.; Patil, S. v. Extracellular Red Monascus Pigment-Mediated Rapid One-Step Synthesis of Silver Nanoparticles and Its Application in Biomedical and Environment. *Bioprocess Biosyst Eng.* **2018**, *41* (5), 715−727.

(157) Venil, C. K.; Sathishkumar, P.; Malathi, M.; Usha, R.; Jayakumar, R.; Yusoff, A. R. M.; Ahmad, W. A. Synthesis of Flexirubin-Mediated Silver Nanoparticles Using Chryseobacterium Artocarpi CECT 8497 and Investigation of Its Anticancer Activity. *Materials Science and Engineering: C* **2016**, *59*, 228−234.

(158) El-Naggar, N. E.-A.; Hussein, M. H.; El-Sawah, A. A. Phycobiliprotein-Mediated Synthesis of Biogenic Silver Nanoparticles, Characterization, in Vitro and in Vivo Assessment of Anticancer Activities. *Sci. Rep.* **2018**, *8* (1), 8925.

(159) Kanmani, P.; Lim, S. T. Synthesis and Structural Characterization of Silver Nanoparticles Using Bacterial Exopolysaccharide and Its Antimicrobial Activity against Food and Multidrug Resistant Pathogens. *Process Biochemistry* **2013**, *48* (7), 1099−1106.

(160) He, S.; Guo, Z.; Zhang, Y.; Zhang, S.; Wang, J.; Gu, N. Biosynthesis of Gold Nanoparticles Using the Bacteria Rhodopseudomonas Capsulata. *Mater. Lett.* **2007**, *61* (18), 3984−3987.

(161) Saberi Riseh, R.; Ebrahimi-Zarandi, M.; Gholizadeh Vazvani, M.; Skorik, Y. A. Reducing Drought Stress in Plants by Encapsulating Plant Growth-Promoting Bacteria with Polysaccharides. *Int. J. Mol. Sci.* **2021**, *22* (23), 12979.

(162) Saberi Riseh, R.; Skorik, Y. A.; Thakur, V. K.; Moradi Pour, M.; Tamanadar, E.; Noghabi, S. S. Encapsulation of Plant Biocontrol Bacteria with Alginate as a Main Polymer Material. *Int. J. Mol. Sci.* **2021**, *22* (20), 11165.

(163) Saberi Riseh, R.; Tamanadar, E.; Hajabdollahi, N.; Vatankhah, M.; Thakur, V. K.; Skorik, Y. A. Chitosan Microencapsulation of Rhizobacteria for Biological Control of Plant Pests and Diseases: Recent Advances and Applications. *Rhizosphere* **2022**, *23*, 100565.

(164) Riseh, R. S.; Hassanisaadi, M.; Vatankhah, M.; Babaki, S. A.; Barka, E. A. Chitosan as a Potential Natural Compound to Manage Plant Diseases. *Int. J. Biol. Macromol.* **2022**, *220*, 998−1009.

(165) Saberi-Riseh, R.; Moradi-Pour, M. A Novel Encapsulation of *Streptomyces Fulvissimus* Uts22 by Spray Drying and Its Biocontrol Efficiency against *Gaeumannomyces Graminis*, the Causal Agent of Take-all Disease in Wheat. *Pest Manag Sci.* **2021**, *77* (10), 4357−4364.

(166) Saberi Riseh, R.; Moradi Pour, M.; Ait Barka, E. A Novel Route for Double-Layered Encapsulation of Streptomyces Fulvissimus Uts22

by Alginate−Arabic Gum for Controlling of Pythium Aphanidermatum in Cucumber. *Agronomy* **2022**, *12* (3), 655.

(167) Pour, M. M.; Riseh, R. S.; Ranjbar-Karimi, R.; Hassanisaadi, M.; Rahdar, A.; Baino, F. Microencapsulation of Bacillus Velezensis Using Alginate-Gum Polymers Enriched with TiO_2 and SiO_2 Nanoparticles. *Micromachines (Basel)* **2022**, *13* (9), 1423.

(168) Pour, M. M.; Saberi-Riseh, R.; Esmaeilzadeh-Salestani, K.; Mohammadinejad, R.; Loit, E. Evaluation of *Bacillus Velezensis* for Biological Control of Rhizoctonia Solani in Bean by Alginate/Gelatin Encapsulation Supplemented with Nanoparticles. *J. Microbiol Biotechnol* **2021**, *31* (10), 1373−1382.

(169) Saberi Riseh, R.; Ebrahimi-Zarandi, M.; Tamanadar, E.; Moradi Pour, M.; Thakur, V. K. Salinity Stress: Toward Sustainable Plant Strategies and Using Plant Growth-Promoting Rhizobacteria Encapsulation for Reducing It. *Sustainability* **2021**, *13* (22), 12758.

(170) Pour, M. M.; Saberi-Riseh, R.; Mohammadinejad, R.; Hosseini, A. Investigating the Formulation of Alginate- Gelatin Encapsulated Pseudomonas Fluorescens (VUPF5 and T17−4 Strains) for Controlling Fusarium Solani on Potato. *Int. J. Biol. Macromol.* **2019**, *133*, 603−613.

(171) Moradi Pour, M.; Saberi Riseh, R.; Skorik, Y. A. Sodium Alginate−Gelatin Nanoformulations for Encapsulation of Bacillus Velezensis and Their Use for Biological Control of Pistachio Gummosis. *Materials* **2022**, *15* (6), 2114.

(172) Fathi, F.; Saberi Riseh, R.; Khodaygan, P.; Hosseini, S.; Skorik, Y. A. Microencapsulation of a Pseudomonas Strain (VUPF506) in Alginate−Whey Protein−Carbon Nanotubes and Next-Generation Sequencing Identification of This Strain. *Polymers (Basel)* **2021**, *13* (23), 4269.

(173) Fathi, F.; Saberi-Riseh, R.; Khodaygan, P. Survivability and Controlled Release of Alginate-Microencapsulated Pseudomonas Fluorescens VUPF506 and Their Effects on Biocontrol of Rhizoctonia Solani on Potato. *Int. J. Biol. Macromol.* **2021**, *183*, 627−634.

(174) Chavez, H.; Nadolnyak, D.; Kloepper, J. Stochastic Frontier Analysis of Biological Agents (Microbial Inoculants) Input Usage in Apple Production. *2012 Annual Meeting*, Birmingham, AL, February 4−7, 2012.

(175) Zaki, O.; Weekers, F.; Thonart, P.; Tesch, E.; Kuenemann, P.; Jacques, P. Limiting Factors of Mycopesticide Development. *Biological Control* **2020**, *144*, 104220.

(176) Pirttilä, A. M.; Tabas, H. M. P.; Baruah, N.; Koskimäki, J. J. Biofertilizers and Biocontrol Agents for Agriculture: How to Identify and Develop New Potent Microbial Strains and Traits. *Microorganisms* **2021**, *9*, 817.

(177) Syed Ab Rahman, S. F.; Singh, E.; Pieterse, C. M. J.; Schenk, P. M. Emerging Microbial Biocontrol Strategies for Plant Pathogens. *Plant Science* **2018**, *267*, 102−111.

(178) Appidi, T.; Pemmaraju, D. B.; Khan, R. A.; Alvi, S. B.; Srivastava, R.; Pal, M.; Khan, N.; Rengan, A. K. Light-Triggered Selective ROS-Dependent Autophagy by Bioactive Nanoliposomes for Efficient Cancer Theranostics. *Nanoscale* **2020**, *12*, 2028.

(179) Appidi, T.; P. S., R.; Chinchulkar, S. A.; Pradhan, A.; Begum, H.; Shetty, V.; Srivastava, R.; Ganesan, P.; Aravind, D.; Rengan, K. A plasmon-enhanced fluorescent gold coated novel lipo-polymeric hybrid nanosystem: synthesis, characterization and application for imaging and photothermal therapy of breast cancer. *Nanoscale* **2022**, *14*, 9112.

(180) Lu, X.; Sun, D.; Rookes, J. E.; Kong, L.; Zhang, X.; Cahill, D. M. Nanoapplication of a Resistance Inducer to Reduce Phytophthora Disease in Pineapple. *Ananas Comosus L.)* **2019**, *10*, 1238.

(181) Tao, J.; Liu, Z.; Zhu, Z.; Zhang, Y.; Wang, H.; Pang, P.; Yang, C.; Yang, W. Electrochemical Detection of T4 Polynucleotide Kinase Activity Based on Magnetic Fe_3O_4@TiO_2 Nanoparticles Triggered by a Rolling Circle Amplification Strategy. *Talanta* **2022**, *241*, 123272.

(182) Lu, X.; Sun, D.; Zhang, X.; Hu, H.; Kong, L.; Rookes, J. E.; Xie, J.; Cahill, D. M. Stimulation of Photosynthesis and Enhancement of Growth and Yield in Arabidopsis Thaliana Treated with Amine-Functionalized Mesoporous Silica Nanoparticles. *Plant Physiology and Biochemistry* **2020**, *156*, 566−577.

(183) Ahmed, T.; Shahid, M.; Noman, M.; Niazi, M. B. K.; Mahmood, F.; Manzoor, I.; Zhang, Y.; Li, B.; Yang, Y.; Yan, C.; Chen, J. Silver Nanoparticles Synthesized by Using Bacillus Cereus SZT1 Ameliorated the Damage of Bacterial Leaf Blight Pathogen in Rice. *Pathogens* **2020**, *9* (3), 160.