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RESEARCH

Algae and cyanobacteria-based biostimulants in controlling plant-parasitic nematodes: a sustainable approach for crop protection

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Abstract Plant root pathogens such as bacteria, fungi, nematodes and viruses infect over a thousand plant species worldwide, threatening the livelihood and food security of small-scale farmers and rural communities who rely on the crops. For centuries, soil fumigants have been the standard for disease infestation control; however, due to the hazardous effects of these fumigants and their overall species specificity failure, there has been a paradigm shift away from using chemicals to control plant pathogens in recent decades. The use of algae and cyanobacteria-based biostimulants in combating plant-parasitic nematodes has recently gained the attention of researchers. This review intends to elucidate the state of the art of algae and cyanobacteria-based biostimulants and their bioactive compounds in controlling plant-parasitic nematodes. In addition, given that the mechanisms of action of these biological biostimulants are not fully understood, this review has further elaborated on how these organisms and their bioactive extracts suppress and control plant pest nematodes. Finally, barriers and prospects in commercializing of algae and cyanobacteria-based biostimulants are reviewed.

Keywords Soil borne pathogens · Root disease · Algae · Cyanobacteria · Biostimulants · Crop protection

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Introduction

Over 80% of food is consumed by people and most of the nourishment for livestock comes from plants. However, the availability and security of plants for human and animal sustenance are frequently compromised by plant diseases and pests (Rizzo et al., 2021). Significant staple crop yield losses can be as high as 30% globally, costing hundreds of billions of dollars in reduced food production (Rizzo et al., 2021). Over a thousand plant species are infected by plant root pathogens such as bacteria, fungi, nematodes, and viruses, endangering the livelihood and food security of small-scale farmers and rural populations who depend on the crops. Plant-parasitic nematodes (PPN) are essential and widespread pests of many plants (Fig. 1). More than 3000 different plant species are affected by PPN (Ralmi et al., 2016). About 10–25% of the world's yearly crop losses are

Fig. 1 Impact of different type of plant-parasitic nematodes infestation on crops; **A** = root-knot nematode, **B** = lesion nematode, and **C**; **D** = cyst nematodes

primarily attributed to plant-parasitic nematodes. Thus, nematodes were responsible for up to 60% of yield losses in infested fields in South Africa. Most of the economic losses are caused by sedentary PPN genera, particularly the root-knot (*Meliodogyne* spp.), lesion (*Pratylenchus* spp.), and cyst (*Heterodera* spp. and *Globodera* spp.) nematodes, which represent a significant constraint (Farmers Weekly, accessed: 13 May 2022).

Root-Knot Nematodes are a significant subgroup of PPNs that are found all over the world. They harm both horticulture and agricultural crops and are obligatory root parasites of thousands of plant species (Kaloshian & Teixeira, 2019). Root galls result from infection, impairing normal nutrition and water intake. As a result, plants develop slowly, reducing quality and production, and cannot withstand other biotic and abiotic stresses (Jagdale et al., 2021). Due to the effects of global climate change, including the emergence of new invasive nematode species and the occurrence of virulent populations able to overcome plant-resistance genes, the economic burden of these parasites is anticipated to continue to rise.

For centuries, soil fumigants have been the standard for disease infestation control in agriculture; however, due to the hazardous effects of these fumigants and their overall specie specificity failure, there is a paradigm shift away from the use of chemicals to control plant pathogens in recent decades. Considering the negative impacts of these products, current regulations are limiting the use of synthetic products in agriculture. Researchers have concentrated their attention on biologically based products in the search for more environmentally-friendly and sustainable ways to increase agricultural productivity, with microalgae and cyanobacteria emerging as valuable resources for both crop production and protection due to their biofertilizing and biostimulating potential (Battacharyya et al., 2015; Chiaiese et al., 2018; Santini et al., 2021). Microalgae and cyanobacteria play a significant part in crop protection because they produce bioactive compounds that stimulate plant development and/or activate plant defense mechanisms in response to biotic and abiotic stressors. Cyanobacterial species are widely known for their beneficial role in agriculture's sustainable microbiome and for their potential to take an active part in crop protection. Algae have long been utilized as fertilizers in agriculture. They are among the organisms that are most frequently utilized in farming as organic fertilizers. These organic biofertilizers supply nitrogen, phosphorus, and organic carbon, which are helpful for boosting soil fertility and the growth and development of plants. A few types of algae also aid in the biocontrol of phytopathogens. As biostimulants that target plant growth promotion and tolerance to biotic (herbivores, fungi, bacteria, viruses) or abiotic (salinity, drought) challenges, algae and cyanobacterial have recently been used for crop production (Sharma et al., 2013; Manjunath et al., 2016). It has to be noted that while some algae-based products may offer nutritional value when used in whole biomass form as agricultural inputs, the commercial seaweed-based or microalgae-based biostimulants discussed in the present review are largely known for their potential to enhance the plant's intrinsic capacity to improve nutrient use efficiency. Given the significance of these findings, the aim of this review is to provide an in-depth analysis of the current state of the art in algae and cyanobacteria-based biostimulants and their bioactive compounds in controlling root-knot and root rot diseases. Furthermore, the present review aims to offer useful insights into the potential of these biostimulants in encouraging healthier crops and more environmentally friendly agricultural practices.

Algae- and cyanobacteria-based biostimulants in controlling root-knot nematodes

Plant pathogens are disease-causing organisms that include various bacteria, phytoplasmas, viruses, nematodes, fungi, and oomycetes (fungal-like creatures). These organisms are widely dispersed in the environment and have the potential to negatively impact the root, stem, leaf, and fruit of several crops in various types of cultivation systems, resulting in considerable economic losses. Plant biostimulants attract interest in modern agriculture to enhance crop performance, resilience to environmental stress, and nutrient use efficiency. Various organic and inorganic compounds, such as humic acids and protein hydrolysates, as well as prokaryotes (such as bacteria that promote plant development), and eukaryotes like mycorrhiza and macroalgae (seaweed), are all included in the category of "plant biostimulants" (Colla & Rouphael, 2020). Because of their adaptability, high photosynthetic efficiency, heterotrophic growth potential, tolerance to domestic and industrial effluent, and antipathogenic, microalgae, which include eukaryotic and prokaryotic cyanobacteria (blue-green algae), are piquing the interest of researchers, private establishments and plant growers. However, few researchers have examined the nematicidal properties of microalgal derivatives or their constituents in inhibiting the plant-parasitic root-knot nematodes.

In vitro bioassay

In vitro bioassays are valuable for evaluating the efficacy of various biostimulants against root-knot nematodes. In the case of controlling root-knot nematodes, in vitro bioassays typically involve culturing nematode populations in controlled conditions and exposing them to different treatments, such as plant extracts, bioactive compounds, or potential nematicides. These treatments can be monitored and measured to impact nematode mortality, development, and reproduction. Ghareeb et al. (2019) investigated the nematicidal effect of three marine algae, *Ulva fasciata*, *Corallina mediterranea* and *Corallina officinalis* extracts on egg hatching and second-stage juveniles (J2s) mortality of root-knot nematode (*Meloidogyne incognita*) under in vitro conditions. The algal strain *U. fasciata* extract significantly increased the mortality rate of J2s after 12, 24, and 48 h, and had the highest activity in suppressing the eggs hatchability of *Meloidogyne incognita* after 3 days with 87% reduction compared to *Corallina mediterranea* and *Corallina officinalis* (Ghareeb et al., 2019). The high nematicidal activity of *U. fasciata* could be because of the polyphenolic and diterpenoids compounds which have antibacterial properties and potential applications (Silva et al., 2013). The aqueous and methanolic extracts of *Oscillatoria* sp. demonstrated nematicidal efficacy against *M. incognita*, according to a similar study by Ghareeb et al. (2022). Their findings also showed that time exposure affected the percentages of mortality and egg hatching in *M. incognita*, with *Oscillatoria* extract showing higher percentages of egg hatching inhibition than Oxamyl and methanol extract (96.7 and 97% after 72 h and 1 week, respectively) and exhibiting higher percentages of mortality after 24, 48, and 72 h, respectively. When compared to the untreated control, a study by Holajjer et al. (2012) showed that *Synechococcus nidulans* had an effect with maximal J2s immobility and mortality of 94.2 and 29.3%, respectively. Also, they found that the egg hatching of *M. graminicola*, *Heterodera cajani*, *H. avenae*, and *Rotylenchulus reniformis* was significantly inhibited. Additionally, Holajjer et al. (2013) noted that a key mechanism governing the immobility or mortality of juveniles inside the egg is the diffusion of toxin molecules or ions through a semipermeable barrier. However, the size, solubility, and chemistry of the solute and the pressure, concentration, and temperature of the molecules or solute, all affect how quickly the toxic molecules move. They also concluded that more research is needed to understand the chemical process of inhibiting egg hatching.

Soil treatment bioassay

The use of cyanobacteria and algae in nematode soil treatment bioassays is an interesting approach that has shown potential for nematode control. The treatment of commercial alkaline seaweed extract (Maxicrop Original®, Maxicrop International Limited) on *Arabidopsis thaliana* plants (grown as monoxenic cultures in Gamborg's B5Medium) significantly reduced the number of deleterious female nematodes (*Meloidogyne javanica*) and number of eggs, compared to untreated plants by 84.1, 87.5, 92.2%, and 93.7%, respectively (Wu et al., 1998). The use of blue-green alga *Oscillatoria* sp. water extract considerably decreased the volume of galls, egg masses, and female nematodes in soybean roots as well as the number of J2s per 250 g soil (Ghareeb et al., 2022). Soybean growth parameters, number of pods/plant, and chlorophyll content were considerably increased by an aqueous extract of *Oscillatoria* (Ghareeb et al., 2022). Featonby-Smith and van Staden (1983) studied the brown alga *Ecklonia maxima* and found that treatment with seaweed concentrate (Kelpak) reduced *Meloidogyne incognita* galling and encouraged the growth of tomato roots. They also found that despite an increase in nematodes in the soil following the application of seaweed concentrate, there were less nematodes in the roots as compared to the control (Featonby-Smith & Van Staden, 1983). A similar study was conducted by Crouch and Van Staden (1993) who reported that soil drench treatment of seaweed concentrate of *Ecklonia maxima*, significantly increased plant growth and reduced infestation by *Meloidogyne incognita* in tomato seedlings. The nematicidal potential of three distinct microalgae, *Scenedesmus obliquus*, *Chlorella vulgaris*, and *Anabaena oryzae*, against *Meloidogyne incognita* on banana (*Musa acuminata)* plants growing in potted soil, were examined in a recent study by Hamouda and El-Ansary (2017). Their findings demonstrated that, when compared to the untreated control, all tested algal considerably resulted in the reduction of second-stage juveniles (J2s) in the soil. In a similar study, El-Ansary and Hamouda (2014) investigated the nematicidal effects of four marine algae species (*Ulva lactuca*, *Jania rubens*, *Laurencia obtusa*, and *Sargassum vulgare*) against *Meloidogyne* spp. infecting banana plants (*Musa* spp.). Their findings showed a much decreased rate of nematode buildup compared to the untreated control. This study also showed that *Ulva lactuca* had the highest nematicidal effect, with a reduction of 73.68% and 56.78% in the number of root galls and the densities of the total population of nematodes, respectively, with stimulated plant growth (El-Ansary & Hamouda, 2014). Furthermore, when compared to the other studied algae and the control, their findings revealed that *U. lactuca* had the most significant total phenolic content, which may account for its effectiveness in reducing root-knot nematode infections (El-Ansary & Hamouda, 2014). El-Ansary et al. (2017) showed that the soil treatment of alginates from *Colpomenia sinuosa, Turbinaria turbinata* and *Cystoseira myrica* significantly reduced the infestation of *M. javanica* (by 80% reduction in egg formation) in eggplant (*Solanum melongena*) roots under greenhouse conditions. According to a greenhouse study by Ghareeb et al. (2019), in contrast to the untreated control, algal extracts from *Ulva fasciata*, *Corallina mediterranea*, and *Corallina officinalis* dramatically reduced the production of galls, egg masses, and J2s densities in tomato roots. The findings also demonstrated that, in contrast to tomato plants infected with the nematode, the activity of the peroxidase and polyphenol enzymes declined in inoculated control plants and remained mostly unchanged in uninoculated plants. The results were similar to those of plants treated with the chemical nematicide oxamyl. Their activities were enhanced in plants treated with algal strain extracts. Numerous studies have revealed a strong correlation between enhanced peroxidase and polyphenol oxidase activities in pest-infested plants and their resistance traits (Kuvalekar et al., 2011; Soffan et al., 2014). Additionally, it has been shown that extracts from some cyanobacteria and other microalgae increased the activity of plant defense enzymes, boosting the plant's resistance (Hamouda & El-Ansary, 2017; Ghareeb et al., 2019). Gall development and nematode infestation were reduced by using dry microalgae powder and cyanobacterial inoculants (Hamouda & El-Ansary, 2017). Certain cyanobacteria have been discovered to break down organophosphorus and other chlorinated insecticides and act as biocidal agents (Subramanian et al., 1994; Kuritz, 1998; Ibrahim et al., 2014). A thorough understanding of nematode ecology, host-parasite relationships, and the dynamics of the entire ecosystem is necessary to develop successful nematode biocontrol strategies using algae and cyanobacteria-based biostimulants. The diversity of nematode species, their life cycles, reproductive patterns, host preferences, and their interactions with plants are the factors that must be taken into account. Yet, as far as we are aware, there is little published material, particularly at the field level, regarding nematode biocontrol. Field-level studies are crucial for evaluating the practicality and effectiveness of these strategies in real-world scenarios.

Mechanism of action of algae and cyanobacteria-based biostimulants on plant-parasitic nematodes

As the world population increases, crop production remains one of the central conundrums facing the human race. Several interventions, especially in chemical control of pathogens, have been employed over the years to ensure food security. However, the health risk records and environmental safety concerns of these pesticides have led to campaigns against the continuous use or application of chemical-based pathogen-controlling agents in agricultural fields (Berthon et al., 2021; Ammar et al., 2022). Thus, the use of more eco-friendlier bio-based measures, such as algae and cyanobacteria biostimulants in controlling or managing root pathogens, appears to be the future of agriculture (Righini et al., 2022). The detailed mode of action of algae and cyanobacteria on root pathogens is largely unknown. However, several authors have tried to make some conclusions. Studies have revealed that cyanobacteria and algae are emerging sources of several phytoactive metabolites, including carbohydrates, amides, amino acids, alkaloids, saponins, terpenes and carotenoids as putative biopesticides which can be exploited in the agricultural industry for the control of PPN (Berthon et al., 2021; Asimakis et al., 2022). For example, Hamouda and El-Ansary (2017) reported that the three microalgae (*Scenedesmus obliquus*, *Chlorella vulgaris* and *Anabaena oryzae*) individually or in combination were able to significantly control the root-knot nematode *M. incognita* (reducing the number of juveniles) in banana. The algae increased the total phenolic content and antioxidant levels in plants which could be the reason for the population decline of *M. incognita.* Two commercial formulations, *Ascophyllum nodosum* (OSMO® (OSMO® International NV, Diksmuide, Belgium) and *Ecklonia maxima* [Kelpak, Kelp Products Ltd., Simon's Town, South Africa) were able to interrupt enzymatic activities of the hatching process and alter sensory perception in tomato (*Lycopersicon esculentum*) roots infected with *Meloidogyne chitwoodi* and *Meloidogyne hapla* (Ngala et al., 2016).

Wu et al. (1998) suggested that the betaines (γ-aminobutyric acid betaine, δ-aminovaleric acid betaine and glycinebetaine) present in the alkaline extract of *Ascophyllum nodosum* (Maxicrop

Original®) induced a defense reaction in *Arabidopsis thaliana* (grown in Gamborg's B5Medium) against root-knot nematodes.

However, more interdisciplinary studies are needed to identify, elucidate and unravel the poorly explored mechanism of action(s) of these putative bioactive antimicrobial extracts/compounds of cyanobacteria and algae origin, which are presumed to be organ, condition and pathogen-specific. The use of microbial (cyanobacteria and algae strains) inoculants as sustainable biofertilizers and biocontrol agents has received substantial attention in some regions of the world (Mahanty et al., 2017; Shah et al., 2021). However, robust global advocacy for environmentally friendly farming practices, such as the inoculation of veritable cyanobacteria and algae strains against root pathogenes, is required to ensure that the versatility of the environment is protected.

The use of synthetic chemicals in managing plant diseases is being vigorously campaigned against (Warra & Prasad, 2020), thus, developing more eco-friendly technology has become an interesting research area (Ghazy et al., 2021). Gold and silver nanoparticles (due to their safety records) can be synthesized using cyanobacteria and algae antimicrobial active principles, which may then serve as potential control agents against plant root pathogens (Terra et al., 2019; El-Sheekh et al., 2021). Furthermore, cyanobacteria and algae antimicrobial activities against plant pathogens have mainly been conducted under controlled laboratory conditions. Therefore, extensive field trials are required to maximize their crop protection potential, especially against more resistant plant root pathogens.

Bottlenecks in the commercial use of algae and cyanobacteria-based biostimulants

The algae and cyanobacteria are by far one of the most diverse groups of organisms, their wide range of physiological and biochemical characteristics makes them ideal sources of many natural products with a wide range of uses (Vu et al., 2018). However, like any other technology in its infancy, many challenges hinder the mass production and commercialization of algae and cyanobacteria-based stimulants. These bottleneck areas include the absence of a standardized cultivation technology (Borowitzka, 2013; De Morais et al., 2015; Vu et al., 2018), lack of techno-economic and ecological analysis for feasibility (Ronga et al., 2019; Alvarez et al., 2021; Perveen et al., 2022), a better understanding of the application techniques (Das et al., 2010; Gülmez et al., 2010), precise molecular mechanisms of action of the products from algae (Holajjer et al., 2013) and limited research on the compatibility of the technology with other pest management technologies (Holajjer et al., 2013).

Lack of standardised production techniques

The use of algae as biostimulants in farming is still in its infancy and strategies for processing and applying algal material are yet to be developed and standardized for nematode management (Rana et al., 2012), while for plant growth and nutrient management, it is well established (Shukla et al., 2019; Shukla et al., 2021; Gupta et al., 2023). Before engaging in the expensive and time-consuming commercial cultivation of algae and cyanobacteria-based biostimulants, it is critical to obtain the right raw material pure or axenic cultures (Vu et al., 2018). A mixture of communities is always problematic in mass production as the organisms may actively compete for nutrients and affect the quality of the produce (Vu et al., 2018). Also, for standardizing production protocols and maintaining the quality of the biostimulant, it is important to accurately identify the best biological producer for a particular biostimulant and adjust its production conditions (Borowitzka, 2013). Cultivation conditions also affect the metabolic pathways of microorganisms; hence, optimization for direct synthesis of specific bioactive compounds needs to be done (de Morais et al., 2015). There are contradictions in the types and quantities of biostimulants produced by the studied algae and cyanobacteria between studies because of non-standard production approaches (Balouiri et al., 2016). Standardization of the cultivation technology will help produce comparable and reproducible results for use in mass production (Das et al., 2010).

Techno-economic and ecological feasibility

The large-scale production of algae and cyanobacteria-based bioactive products is economically unfeasible (Alvarez et al., 2021). Performing detailed techno-economic and ecological analysis is important if the mass production of biostimulants is to be sustainable (Bravo-Fritz et al., 2016). The economic and the ecological feasibility of production of biostimulants used in crop protection has not been done, while according to Bravo-Fritz et al. (2016), working on the potential of algae as an alternative to fossil fuel in energy production indicates that the current technology of algae production is still not sustainable. Ronga et al. (2019) also reported the same when algae were used as biofertilizers, concluding that the production process could be more economically competitive than the commercial fertilizers when algae was used as an alternative source of nitrogen fertilizer for plant growth. There still exists multiple challenges in the economic viability of significant production of algae and cyanobacteria-based bioactive products, with most of the costs coming from production costs (Thomassen et al., 2016). Advancing technological improvements for economically feasible, large-scale production of quality biostimulants is still required (Thomassen et al., 2016). There are three significant ways in which the production costs of algae could be minimized. Firstly, since algae are versatile and grow in a broad range of nutrient sources, the use of wastewater streams would decrease the costs and environmental impacts of algal cultivation (Daneshvar et al., 2018; Alvarez et al., 2021). Secondly, instead of focusing on the production of one product, multiproduct biorefinery could prove much more economical (Lam et al., 2018; Yadav & Sen, 2018). Algae and cyanobacteria have a wide range of physiological and biochemical characteristics, that can naturally produce many different bioactive compounds (Perveen et al., 2022). Unfortunately, currently, a technology to access all different product fractions from algae does not exist; hence a lot of valuable components are discarded or remain undervalued (Lam et al., 2018). Lastly, crude material from algae could be applied as soil amendments to manage soil borne plant pathogens (Alvarez et al., 2021). The application of biostimulants as soil amendments will cut the costs of biorefining the material for producing specific biostimulants (Postma et al., 2017).

Application techniques

With most of the studies of biostimulant compounds done in vitro, the development of active compounds is only complete once the applicability of such products is tested under field conditions (Das et al., 2010). In vitro studies lack the effects of host response and the impact of soil physical, chemical, and biological properties on the efficacy of the biostimulants in their use in controlling soilborne diseases (Gülmez et al., 2010). Suitable field markers are required to evaluate the efficacy of bioactive compounds from biostimulants and their modification in different soil types (Alvarez et al., 2021). There is a need to evaluate different methods and timing of application/dispersal of biostimulants, whether it be soil drenching or foliar application before, after or during planting; the best-used equipment for the dispersal, should be formulated as a slow release or not (Yan et al., 2013).

Compatibility with other technologies

Algae and cyanobacteria-based biostimulants have great potential to be used in agriculture. However, the exact mechanisms of how these biostimulants interact with plants and soil are not yet fully understood. The use of algae and cyanobacteria-based biostimulants needs more information on potential synergistic effects or their interaction with other beneficial soil organisms on plant growth and soil health (Holajjer et al., 2013; Alvarez et al., 2021). Studies on the effects of biotic and abiotic soil properties on the performance of these biostimulants still need to be investigated to better understand the impact of these microorganisms on plant growth and soil health. Endophytes may be important in this process as they can interact with algae and cyanobacteria-based biostimulants, further influencing their effects on plant growth and soil health. Investigating the interactions between different microbes may help us understand the overall effect of algae and cyanobacteria-based biostimulants on plant-soil systems.

Future prospects

The future prospect of technology is entwined with its ability to meet the ever-changing technological, social, ecological, and economic environments and the maximum exploration of the full potential of that technology. Compared to about 250,000 species of higher plants, several million species of algae and cyanobacteria are believed to exist. However, only a few hundred have been investigated (Coêlho et al., 2019). Thus, many bioactive compounds remain in these organisms that have not yet been identified

(Lam et al., 2018). Large-scale screening of algae and cyanobacteria could yield many bioactive chemicals with potential uses in crop protection and many other industries (Perveen et al., 2022).

The prospects of algae and cyanobacteria in crop protection are enormous and is becoming even greater in the developing world. These include (i) advancing technology to make algae and cyanobacteria production economically sustainable, environmentally, and socially feasible for large-scale production, (ii) future research in large-scale production technologies, formulation, and delivery could greatly assist in commercialization (Holajjer et al., 2013). (iii) Algae and cyanobacteria provide novel methods to develop micronutrient-dense staple crops in addressing the malnutrition prevalent in many developing countries. The technology could be borrowed from the use of microalgae in the biofortification of crops (Rana et al., 2012). (iv) Genetic engineering of algae and cyanobacteria to produce more bioactive compounds can be undertaken (Holajjer et al., 2013). This could increase productivity and reduce technology production costs (Rajneesh et al., 2017). (v) Identification of the molecular mechanism of biological algae and cyanobacteria compounds on soilborne diseases could result in efficient use of the products to control the pests (Holajjer et al., 2013). (vi) Nanotechnology has recently been used to successfully manage pest-infected plant crops (Prasad et al., 2021; Yan et al., 2013). The nano-encapsulation of biological materials, such as those from algae and cyanobacteria, could be beneficial in avoiding the use of hazardous chemical pesticides and offers several benefits over chemical synthesis, including eco-friendliness and compatibility with other pest management tactics (Saratale et al., 2018). (vii) Combination of algae and cyanobacteria-biostimulants with other biologically active compounds to improve the performance of the product. Yan et al. (2013) reported that coating cyanobacteria powder with Carbopol reduced pesticide adsorption resulting in a slow-release formulation.

Conclusions

Due to the substantial limitations placed on the use of chemical pesticides, current control technologies need to be improved to enable the proper management of root parasites. Therefore, it is critical to identify new possible pesticidal sources that can be used to create novel, secure, and efficient control methods. Using algae-based or cyanobacterial-based biostimulants may reduce the dependency on synthetic nematicides for the sustainable management of root pathogens. However, previous studies have demonstrated the capabilities of algae and cyanobacteria as biofertilizers and biocontrol agents. However, when using these organisms or their extracts/compounds, it is essential to optimize (e.g., standardization of active doses, time of application, mode of application) them for particular crops. The current review highlighted the potential use of algae- and cyanobacteria-based biostimulants along with their bioactive compounds managing of root pathogens. However, there are still gaps that need to be filled, necessitating the use of numerous empirical trials that will facilitate its use in the field settings and increase mass crop production.

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Authors' contributions Sithole N and Gupta S: Conceptualization, data curation, investigation, writing – original draft, and editing; Dube Z and Ogbe A: data curation and review, Gupta S and Van Staden J: funding acquisition; Van Staden J: Supervision, project administration, review and editing. All authors have read and approved the final manuscript for publication.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

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