Review

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Purpureocillium lilacinum for Biocontrol, Bioremediation and Biofertilization

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Purpureocillium lilacinum for Biocontrol, Bioremediation and Biofertilization

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Abstract: *Purpureocillium lilacinum* PL11 (formerly *Paecilomyces lilacinus*) is a ubiquitous fungus found in several habitats, mainly in the soil, and belongs to the Ophiocordycipitaceae family. This fungus was shown to have potential applications in agriculture as a biocontrol agent and biofertilizer. *P. lilacinum* can inhibit plant–pathogenic fungi and nematodes, including root-knot and potato cyst nematodes. Additionally, *P. lilacinum* produces siderophores and indole-3-acetic acid (IAA), enhancing plant development and increasing soil nutrient availability. *P. lilacinum* has been extensively studied in various commodities, including pineapple, maize, soybean, and legume. Most studies have evaluated *P. lilacinum* as a biocontrol agent, especially for nematode control. Other studies have evaluated the production of secondary metabolites and bioremediation, and few studies have used this fungus as a plant growth promoter. This review addressed important aspects of using this fungus. *P. lilacinum* is a promising fungus that can be used for agricultural production, reducing environmental impact, and thus collaborating for a sustainable agriculture production system.

Keywords: sustainability; plant production; fungus; crop production

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Introduction

Utilizing biological inputs to enhance plant growth is highly advantageous in promoting sustainable agriculture [1]. Understanding the advantages of microbial isolate applications on plant growth remains inadequate. Consequently, it is imperative to understand the impact of soil inoculation to establish a comprehensive repository of information that can be utilized to devise sustainable agricultural methodologies [2]. Healthy soil for growing crops is influenced by biological agriculture farming techniques, weather factors, and nutritional and biological parts. One possible way to improve soil nutrients and plant health is using biofertilizers. Biofertilizers can be made of bacteria and fungi, making nutrients available to plants through organic processes [3]. Some fungal isolates change the soil by making nutrients more soluble and helping plants grow. However, when used, little is known about how these isolates affect soil biology and nutrition. The most noticeable effect of fungi that helps plants grow is that roots and shoots gain more weight. These benefits may come from how the fungus makes and controls the production of phytohormones. Fungal treatments can help control root growth factors such as ethylene, indole-3-acetic acid, abscisic acid, salicylic acid, and jasmonic acid [4]. Fungi can also be used for nematode control [5], insect control [6], and the production of secondary metabolites [7], which affect the growth of several phytopathogens, and this fungus can be used to ameliorate soil contamination through the process named bioremediation [8] and can stimulate plant growth due to several mechanisms of action [9]. This review addresses current studies regarding the utilization of the fungi *P. lilacinum* for these skills.

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Purpureocillium lilacinum for biocontrol

Entomopathogenic fungi may reduce nematode and insect populations [10]. These fungi can be used as biocontrol agents, reducing the damage caused by these nematodes, including *Meloidogyne incognita,* which causes significant damage to several crops [11]. The effectiveness of using these kinds of fungi has been investigated and has been promising for several important agricultural crops worldwide [2,9,10,12] . The use of *P. lilacinum* has been combined with some chemical nematicides; for instance, a chemical nematicide named Velum and a biological nematicide produced by *P. lilacinum* combined to regulate the root-knot worm *M. incognita* in tomato plants have been investigated. Their results showed that combining both nematicides was more successful than using either nematicide separately in decreasing worm numbers and increasing tomato output [13]. The nematicide Velum successfully reduced the worm population at sowing and sustained *P. lilacinum* biological activity throughout the growing season. The combination of *P. lilacinum* and the nematicide Velum resulted in the greatest decrease in the second-stage juvenile population, followed closely by Velum alone, which resulted in a 92% reduction in second-stage juveniles. The second-stage juvenile population was decreased by 61% by *P. lilacinum*. The fungus *P lilacinum* is able to control *M. incognita* worms. During a two-year indoor tomato-cucumber cycle, researchers tested the effectiveness of using both vigorous tomato plants and the fungus *P. lilacinum* to control *M. incognita* worms. Worm populations and crop losses might be reduced with just plant resilience [5]. This type of study is significant because it demonstrates the possibility of combining the effectiveness of chemicals and fungi, which improves the results compared to using them separately. Additionally, this study showed that some chemical nematicides are compatible with *P. lilacinum*. Fungal inoculation causes a reduction in egg viability, which leads to nematode control. In vitro, the fungus parasitized 94.5% of eggs, but not embryos, and had protease, lipase, and chitinase activities [14]. An important aspect to consider for nematode control is the impact of water stress and temperature on the growth and enzymatic activity of *P. lilacinum.* This fungus can combat *Nacobbus aberrans*, a type of plant-parasitic nematode. The fungus exhibited the ability to thrive under varying levels of water stress, but its growth rate decreased as water stress levels intensified. In addition, under inductive conditions, the fungus produced chitinases, proteases, and leucinostatins. The study concluded that *P. lilacinum* was a useful biocontrol agent for phytoparasitic nematodes in tomatoes under various agroecological conditions. Additionally, *P. lilacinum* demonstrated saprophytic soil colonization ability and displayed endophytic potential in tomato plants [15]. The formulation of biological products is important because it can significantly impact the effectiveness of fungi in controlling nematodes. Therefore, extensive studies focusing on the compatibility between the fungus and the formulation are necessary before creating a new product. Such studies are crucial to ensure that the new product will be effective in controlling nematodes and to prevent any reduction in efficacy due to compatibility issues between the fungus and the formulation. A new bioformulation of *P. lilacinum* for managing plant-parasitic nematodes has been tested. *Karanja deoiled* cake (KDG) and sundried biogas sludge (BGS) were evaluated as a mixed base to create a bioformulation for plant-parasitic nematodes. *P. lilacinum* spores with improved virulence were mass-produced using optimum food sources. KDC-BGS base with *P. lilacinum* controlled worms in wheat better than *P. lilacinum* alone. Controlling plant-parasitic nematodes with the KDC-BGS base bioformulation with *P. lilacinum* was eco-friendly and cost-effective [16]. This study has shown the importance of the bioformulation for the effectiveness and efficiency of the use of *P. lilacinum* for biocontrol. Another possibility to inoculate *P. lilacinum* is using liquid formulations to apply biological agents for agriculture: liquid formulations are easy to handle and apply. They can be easily sprayed onto crops using conventional spraying equipment, making them a convenient option for farmers. Liquid formulations can provide better crop coverage than other formulations, such as powders or granules. This is because they can be applied evenly and can penetrate the plant tissue more effectively, increasing the efficacy of the biological agent. Liquid formulations can have a longer shelf life than others, as they are less susceptible to environmental conditions such as humidity and temperature. This can result in a more stable and effective product, reducing the need for frequent replacements and saving costs for farmers. Finally, liquid formulations can be easily mixed with other agricultural inputs, such as fertilizers, herbicides, or insecticides, allowing farmers to save time and reduce the number of applications needed. This also reduces the potential for phytotoxicity or negative interactions between products [17]. Liquid formulations have been evaluated using three biocontrol agents, *Pseudomonas fluorescens*, *P. lilacinum*, and *T. viride,* against potato cyst nematodes under field conditions. The biocontrol agents were administered as seed treatment and soil drenching. Their efficacy was compared with that of carbofuran. The findings indicated that all three biocontrol agents effectively reduced cyst nematode eggs and density, root penetration, and egg numbers cyst-1, with varying degrees of efficacy based on their application method. *P. fluorescens* was the most effective in reducing egg density, multiplication rate, root penetration, and egg numbers cyst-1, followed by *P. lilacinum*. The potato plants treated with *P. fluorescens* and *P. lilacinum* were taller and had higher tuber yields than untreated plants. *P. fluorescens* showed higher root colonization in cyst nematodes than *T. viride*, while *P. lilacinum* showed the opposite trend. The biocontrol agent efficacy was comparable to that of carbofuran. In conclusion, *P. fluorescens* and *P. lilacinum* applied through seeds as liquid formulations were highly effective for managing cyst nematodes under naturally infested field conditions [11].

Eggplant is an important crop for many farmers and communities around the world. It is a high-value crop that can provide a source of income for small-scale farmers, and it is often grown in areas with limited water resources or poor soil quality, where other crops may struggle to thrive [18]. *P. lilacinum* may control several plant pathogens in eggplants, and some studies have shown that its effectiveness relies on the dose. An in vitro study using eggplants showed that *P. lilacinum* significantly reduced the rates of egg hatching and juvenile survival of *M. incognita* in a dose-dependent manner. Interestingly, *P. lilacinum* penetrated the eggs and promoted damage in the juvenile, indicating its high potential for controlling this parasite. The results indicated that *P. lilacinum* could be used as a biological control for reducing diseases caused by nematodes in eggplants [19]. An excellent strategy to improve the effectiveness of *P. lilacinum* to control nematodes is its inoculation mixed with other fungi. An interesting fungus that may be inoculated with *P. lilacinum* has been *Trichoderma* due to its synergistic potential to control nematodes and its compatibility with *P. lilacinum*. A study has shown that three *Trichoderma* strains and two *P. lilacinum strains* may be used against *M. javanica*, a plant-parasitic worm that reduces pineapple output. Pineapple is an important crop in agriculture due to its economic, nutritional, adaptability, environmental, and cultural benefits [20]. Two *Trichoderma* and two *P. lilacinum* strains substantially lowered nematode egg and egg mass production, reducing root galling harm and increasing plant root mass growth. *Trichoderma asperullum and P. lilacinum* strains reduced galls, egg mass, and ova. *Trichoderma atroviride* did not impact worm growth or root damage, unlike the control *T. asperellum*. and *P. lilacinum* strains from pineapple can, directly and indirectly, impact worm growth and host response, suggesting that they may inhibit *M. javanica* [21].

Soybean is an essential crop worldwide, and its grains are a primary source of protein and oil for both human and animal consumption and are used to make a variety of food products, including tofu, soy milk, soy sauce, and vegetable oil, which are consumed around the world. Soybean is also a key ingredient in livestock, poultry, and aquaculture animal feed. It is a cost-effective source of protein and essential amino acids for animal growth and health. Soybean is one of the most widely traded crops in the world, with major producers including the United States, Brazil, and Argentina. Soybean exports generate billions of dollars in revenue yearly, with China being the largest importer of soybeans [22]. However, it is susceptible to various types of nematodes that can cause significant harm and reduce its productivity, resulting in substantial financial losses. Mixtures of *P. lilacinum*, *Claroideoglomus etunicatum*, and *Rhizophagus clarus* were evaluated against *M. incognita* in soybean under greenhouse conditions. Twelve indigenous fungal and bacterial rhizosphere isolates were tested against the root-knot nematode *M. graminicola*. Research has shown that biocontrol agent culture filtrates impede egg hatching and kill nematode juveniles [10]. Another important crop is rice. Rice is a staple food for over half of the world's population, particularly in Asia and Africa. It provides a significant source of calories, carbohydrates, and nutrients, such as vitamins and minerals, essential for human health. Rice production and trade are significant contributors to the global economy. This

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cereal is one of the most important crops for small farmers in developing countries, providing income and employment opportunities. In addition, rice exports generate billions of dollars in revenue each year for major producers such as Thailand, Vietnam, and India. Rice cultivation can have positive environmental impacts, as it can help prevent soil erosion, promote biodiversity, and conserve water resources through efficient irrigation practices [23]. The mixture of microorganisms has also been evaluated in rice crops. The six most effective biocontrol agents have been tested regarding their potential for reducing nematode damage and boosting plant growth and yield. *Pseudomonas putida* controlled root-knot disease best of the biocontrol agents evaluated. *T. harzianum* colonized *M. graminicola* eggs, juveniles, and adult females the most, followed by P. *lilacinum*. *Bacillus subtilis* had limited impacts. *P. putida*, *P. fluorescens*, and *T. harzianum* had the highest rhizosphere population increase. In naturally infected areas, *P. putida* and *T. harzianum* controlled *M. graminicola* and improved rice tillering and yield. *Pseudomonas putida* and *T. harzianum* are potential biocontrol agents for controlling *M. graminicola* in rice crops [24]. Endophyte fungi have the potential to not only enhance plant growth but also act as natural pest control agents by reducing the survival rate of insect pests. Numerous endophytic fungi exhibit entomopathogenic abilities and are currently being utilized for insect control, such as *P. lilacinum*. However, limited information is available regarding the potential use of *Beauveria bassiana* with *P. lilacinum*, known for its insecticidal properties, which can reside within plants without causing any harm. The presence of these fungi in cotton plants positively impacted their growth and made it difficult for insects to survive on them. This indicates that these fungi could be a sustainable and effective alternative for protecting crops from insects. The results suggest that manipulating fungal endophytes could be valuable in integrated pest management strategies prioritizing sustainability [6].

Fungal endophytes can shield plants from a variety of stresses, including pests. Entomopathogenic fungal endophytes are the term given to this fungus, and the biological functions these fungi can perform are significant in farming systems. Entomopathogenic fungal strains have been found in several plants, and a single isolate can be introduced to develop as an endophyte across a range of plants [6]. According to [25], these entomopathogenic fungal endophytes are categorized as nonclavicipitaceous, which refers to fungal endophytes that are typically spread laterally. Many nonclavicipitaceous entomopathogens, such as *Beauveria bassiana*, *Lecanicillium lecanii*, *Metarhizium anisopliae*, and *Isaria* (*Paecilomyces*) spp., may combat plant diseases in planta and promote plant development. The impact of *P. lilacinum* and *B. bassiana* fungi that potentially benefit soil and plant health in sandy and clayey soils from the Brazilian Cerrado has been examined. In a greenhouse, assays were conducted using corn and soybean plants. The study findings suggest that applying these fungal isolates can benefit soil function and quality in the medium to long term. These positive impacts could lead to the development and adoption of more sustainable agricultural practices, which is of significant importance [26]. To evaluate the potential use of *P. lilacinum* against insects, this fungus was tested for its ability to manage the *Thai orchid* bug *Thrips palmi*. A study showed that *P. lilacinum* could biocontrol *Thrips palmi* in Thai flower farms. After four applications, both *P. lilacinum* therapies considerably reduced thrips. Other biocontrol drugs, imidacloprid, and the water + clay control did not significantly affect the thrips population. In the field test, the water + clay solution killed some thrips, probably due to clay particle tips wounding the insect skin [27].

The cotton crop is an important crop due to its economic, cultural, and social significance. Its fibres are used in the textile industry, it provides income for millions of farmers, and its byproducts are used for food and animal feed. Additionally, cotton production can support biodiversity and promote sustainable agriculture practices [28]. An important insect that promotes high production losses in cotton crops is *Helicoverpa zea* larvae. *P. lilacinum* has also been explored due to its potential to control insects when inoculated with other fungal endophytes, particularly *Beauveria bassiana,* to improve cotton growth and reduce the survival rate of *Helicoverpa zea* larvae. The researchers observed that these endophytes, once introduced into cotton plants, adversely impacted the survival of larvae that consumed them. Consequently, the authors proposed that manipulating fungal endophytes could significantly impact sustainable integrated pest management practices [6].

Most entomopathogenic fungi infect and ultimately destroy insects and other arthropods via conidia that adhere to the cuticle and hyphae that penetrate the cuticle following conidial germination. It is extremely uncommon for insects to become infected via the digestive tract after ingesting spores. Upon the demise of a host, new spores are typically produced on the corpse and disseminated into the adjacent environment [29]. *P. lilacinum* has been tested as a biological control agent of several insect pests. For example, it was demonstrated that this fungus was able to control leaf-cutter ants. The inoculation of this fungus significantly reduced the survival of ants from six *Acromyrmex lundii* field colonies, with a median lethal time of 6-7 days. The fungus was responsible for 85.6% of the mortality in inoculated ants and showed a good competitive capability against other entomopathogens that naturally infected ants. Horizontal transmission to noninoculated ants was also observed. The study proposes the use of *P. lilacinum* as a potential biological control agent of leaf-cutter ants in crops and plantations [30]. *P. lilacinum* can be used to control another important insect that causes great economic losses. For instance, the pathogenicity of *P. lilacinum* isolated from Egypt was evaluated against four pests, *Bemisia tabaci*, *Tetranychus urticae*, *Thrips tabaci*, and *Diuraphis noxia*. The fungal filtrate had a higher toxic effect on all tested pests than the spore suspension. The greater fungal filtrate concentration resulted in higher mortality rates seven days posttreatment, reaching 100% for *T. tabaci and T. urticae* and 97% for *B. tabaci* and *D. noxia* [31]. The fungus *P. lilacinum* has proven to be a highly effective biocontrol agent against a broad spectrum of insects, including the tomato leafminer pest. This is an interesting finding that highlights the potential of this fungus as a natural solution for pest management [32].

Purpureocillum lilacinum is a fungus that produces a variety of secondary metabolites with potentially important applications in medicine, agriculture, and industry. Some of these secondary metabolites have been found to possess antimicrobial, anticancer, and antiviral properties, making them promising candidates for developing new drugs [33]. Plants and microbes only create secondary metabolites during certain stages of development. Pigments, hormones, poisons, and antibiotics are all tiny molecules with complicated chemical structures that are not essential for normal development and reproduction [34]. *Purpureocillum lilacinum* has been identified as a great producer of leucinostatin D, acremoxanthone G, and acremonidin. Leucinostatin A, B, C, and D are considered biologically active secondary metabolites. They were found to be effective against a wide variety of yeasts, both pathogenic and nonpathogenic, as well as filamentous fungi, and to have moderate activity against gram-positive bacteria. In addition to secondary metabolites with potential use in biotechnology, the fungus also produces a substance of agricultural importance [7]. The effects of two secondary metabolites produced by *P. lilacinum*, indole-3-carboxaldehyde and indole-3-carboxylic acid, on regulating tobacco mosaic virus have been evaluated. In vitro and in vivo, these secondary metabolites demonstrated potent antiviral activity. They split virus virions and caused the fragmented particles to clump together. Virus application also caused immunological reactions or resilience to virus infection in tobacco, including the expression of hypersensitive reactions, increased defense-related enzymes, and overexpression of pathogenesis-related proteins. The increase in the salicylic acid biosynthesis of several genes showed that salicylic acid functioned as a defense-related signaling molecule in plants. As a result, indole compounds can activate tobacco defenses against mosaic viruses and other viruses and can be used for disease management [35]. Various food-grade antioxidants and natural polyphenols are compatible with *P. lilacinum*. The most suitable compounds with the 21 genotypes of *P. lilacinum* were found to be 2(3)-tert-butyl-4 hydroxyanisole (BHA), 2,6-di(tert-butyl)-p-cresol (BHT), 3-phenyl-2-propenoic acid (CA), and the mixture of BHA and BHT. Furthermore, certain types develop better in the presence of certain therapies. The effect of these compounds and entomopathogenic fungus mixtures on *Aspergillus flavus* growth metrics and toxin generation in vitro was also investigated. The study found that combining entomopathogenic fungus with BHA (1 mM) enhanced the latency period and reduced the *Aspergillus flavus* growth rate and aflatoxin B1 generation at three water activities evaluated. These results imply that combining food-grade antioxidants and natural polyphenols with entomopathogenic fungi could be a successful and long-term approach to managing aflatoxin-producing fungi [36].

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Purpureocillium lilacinum as biofertilizer

Some *P. lilacinum* strains present several characteristics related to plant growth promotion. However, few studies have been carried out showing these abilities. This fungus is a promising microorganism that can be used for this purpose. A study with maize, bean and soybean evaluated the potential of *P. lilacinum*, *Purpureocillium lavendulum*, and *Metarhizium marquandii* as plant growth-promoters. The researchers tried the most promising fungi in greenhouse trials for their ability to solubilize phosphorus and make indoleacetic acid (IAA). Some breeds boosted phosphate and nitrogen supply and affected plant growth metrics differently for each crop. However, field changes did not always match in vitro changes. In conclusion, these fungi may be used as bioinoculants for agricultural plant growth [9]. The effects of five beneficial nonmycorrhizal fungi with *P. lilacinum* on soil and plants in sandy and clayey soils from the Brazilian Cerrado were investigated. The study was conducted under corn and soybean plants in greenhouse assays. The results indicate that applying these fungal isolates can positively impact soil function and quality in the medium and long term. This could ultimately contribute to developing and adopting more sustainable agricultural practices [12]. Another study investigated the effects of five fungal endophytes, including *P. lilacinum,* on the growth, biological, and chemical properties of rhizosphere soil under *Phaseolus vulgaris* L. The study aimed to identify the impact of fungal isolates on plant growth and soil fertility and to highlight the benefits of using these treatments in reducing the environmental impacts of mineral fertilizers and pesticides in sustainable agriculture. The report also discusses the role of plant growth-promoting fungi in regulating phytohormones and contributing to plant growth. The findings suggest that fungal isolates can enhance soil fertility and promote plant growth, making them valuable in sustainable agricultural management systems [4]. *P. lilacinum* can improve soil nutrients and plant growth with biofertilizers. Biofertilizer microorganisms that increase nutrient availability through biological processes were assessed for *Capsicum chinense* plants, focusing on *P. lilacinum*. *P. lilacinum* solubilized basic P sources and produced siderophores and indole-3-acetic acid in this study. *P. lilacinum* also affected greenhouse plant growth, crop quality, and yield. *P. lilacinum* solubilized $Ca_3(PO_4)_2$ better than $FePO_4$, creating siderophores and IAA. *P. lilacinum* boosted *Capsicum chinense* plant height, stem girth, and foliar P. Inoculated plants had heavier fruit and larger lengthwise diameters. Fruit yield remained unchanged. This work shows that *P. lilacinum* biofertilizer improves *C. chinense* plant growth and nutrient intake [3].

Purpureocillum lilacinum for bioremediation

Purpureocillum lilacinum can be used for bioremediation, reducing soil pollution. It is a good strategy to decrease environmental impacts and improve soil degradation. A mixture of *P. lilacinum* and *Penicillium chrysogenum* has been studied for the bioremediation of heavy oil waste. When fed carbon and nitrogen, these fungi biodegrade oil waste compounds. Fungal therapy altered hydrocarbon component abundances. *P. lilacinum* degraded 100% cycloalkanes, 21.2% n-alkanes, 15.1% aromatics, and 14.5% iso-alkanes. *P. chrysogenum* altered the hydrocarbon makeup differently. It decreased n-alkanes (1.3%) and increased cycloalkanes (82.6%), aromatics (10.2%), and iso-alkanes (11.9%). *P. lilacinum* and *P. chrysogenum* also cleared 15.3% and 7.6% of the changed oil sludge's petroleum compounds, respectively. These findings demonstrate that *P. lilacinum* and *P. chrysogenum* can bioremediate oil sludge-contaminated soils by degrading hydrocarbons [37]. Another study investigated the impact of copper addition to soil on the growth and physiology of *Sedum alfredii*, a type of plant. The findings reveal that adding copper to the soil led to increased copper accumulation in the plant, with variations in copper content observed between the aboveground and belowground parts of the plant. Additionally, the study assessed the chlorophyll content and water status to evaluate their physiological response to copper exposure [38].

Mechanisms of action

As previously mentioned, the fungus *P. lilacinum* has shown great potential as an endophyte and entomopathogenic fungus with numerous applications in biotechnology and agriculture. Various studies have highlighted its abilities, including biocontrol, biofertilization, and bioremediation, achieved through different modes of action. In the case of biocontrol of nematodes, the fungus produces various enzymes, including chitinases and proteases, which digest the chitin and proteins in the nematode's body, leading to its death [39]. Moreover, this fungus is capable of reducing the incidence of phytopathogenic fungi by damaging their cell membranes and components, ultimately leading to their demise [40]. Furthermore, during certain stages of fungal development and under appropriate environmental conditions, *P. lilacinum* produces secondary metabolites by expressing specific genes, which are then released into the environment. These molecules have various applications in biotechnology and medicine [7]. In Figure 1, a schematic representation of the isolation, identification, and various uses of *P. lilacinum* in agriculture is presented. Figure 2 shows the evaluations regarding the inoculation of *P. lilacinum* in the plants with two modes of application in the crops. Table 1 displays several abilities of *P. lilacinum*, including its ability to control phytopathogenic fungi, promote plant growth, and produce secondary metabolites.

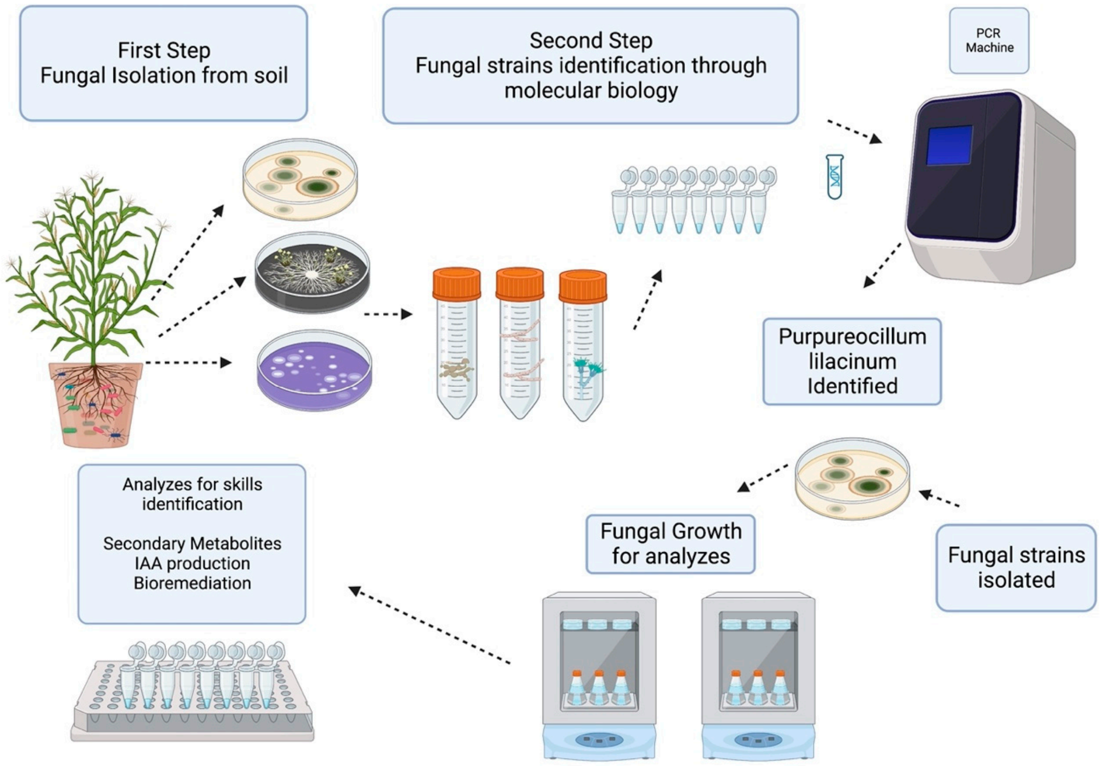

Figure 1. Schematic representation of the steps in which the fungus was isolated from soil samples in the first phase. The isolates were removed from the pure culture (isolated) in the second phase. In the third phase, the fungus was identified as *Purpureocillum lilacinum* using molecular biology. The fungal strain was then cultured in liquid medium to test its capacity to create indol acetic acid and secondary metabolites, as well as its ability to detoxify soil and water through bioremediation.

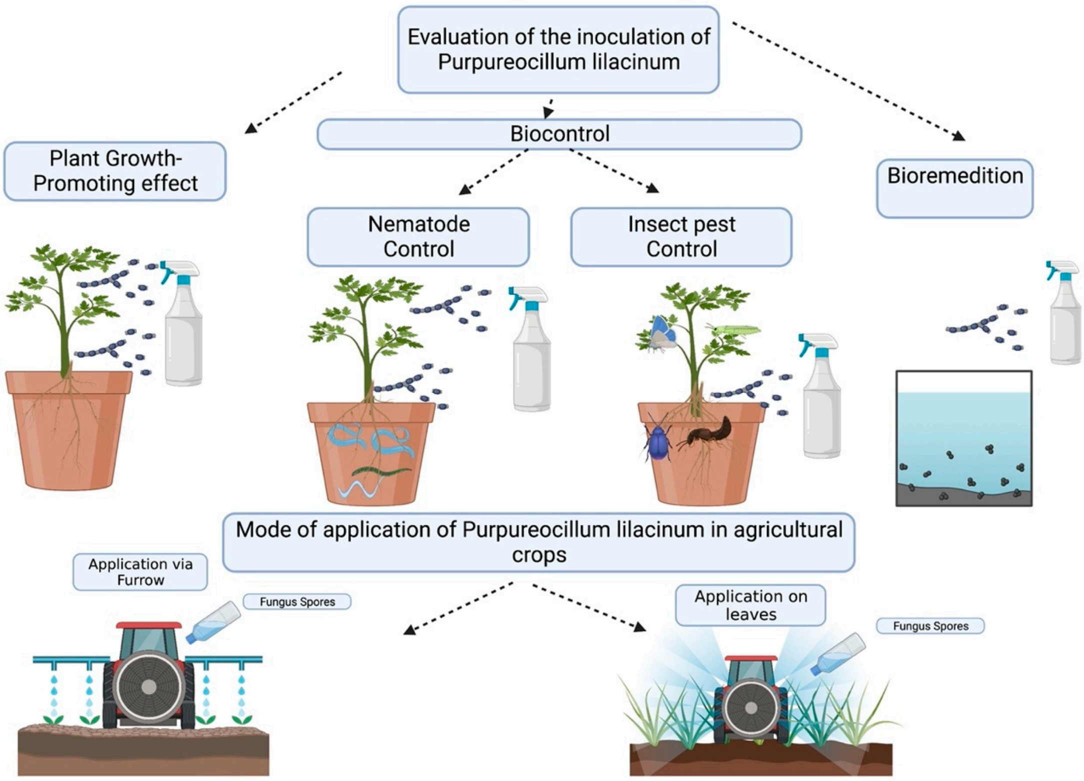

Figure 2. The fungus was cultured in liquid media and then applied to plants to test and assess its influence on plant growth. The fungus was also sprayed on plants to assess its biological control impact in lowering the occurrence of nematodes in the soil. In addition, the fungus was administered to the plant to verify and assess pest control. Finally, the fungus was introduced to water and soil to test its bioremediation impact. The modes of application might be furrow straight into the soil or areal application on the leaves.

Table 1. *Purpureocillum lilacinum* abilities to control phytopathogen fungi, secondary metabolites production and plant growth promoting.

Kind of Effect	Results	References
Nematode Control	Control of root-knot nematodes in tomatoes	Kepenekci et al., 2018
	Control of *Meloidogyne javanica* in commercial pineapple	Kiriga et al., 2018
	The fungus showed maximum egg mass inhibition of *Meloidogyne incognita*	Sharma et al., 2021
	Reduction of *Meloidogyne incognita* in tomatoes	Dahlin et al., 2019
	The fungus was effectively applied as biocontrol agents of phytoparasitic nematodes in tomatoes under variable agroecological conditions.	Girardi et al., 2022
	Suppressed nematode *Meloidogyne incognita* population in a tomato–cucumber rotation in a greenhouse	Giné and Sorribas, 2017
	The fungus controlled root-knot nematodes infecting eggplant	Khan and Tanaka, 2023
Secondary Metabolites	Production of indole-3-carboxaldehyde (A1) and indole-3-carboxylic acid for tobacco mosaic virus control	Sun et al., 2022
	Production of metabolites for biological control	Chen and Hu, 2021
	Proteases production	Chen and Hu, 2021

Biological Control	Controlled the insect *Thrips palmi* in orchid farms	Hotaka et al., 2015
	Potential control against cotton aphids	Castillo Lopez et al., 2014
Plant-Growth	In soybean stimulated root growth and nutrient absorption	Barbosa et al., 2022
	Increased the availability of P and N and promoted the growth of maize, beans and soybean	Baron et al., 2020
	Improved soil nutrient availability in common bean growth	Alves et al., 2021
	Promoted significant increases in plant dry biomass in cotton crop	Lopez and Sword, 2015
Bioremediation	Reduced the amount of total petroleum hydrocarbons in contaminated soils	Yang et al., 2023
	Removed 44.55% of crude oil from contaminated soil	Benguenab and Chibani, 2021
	Protected mangrove plant *Kandelia candel* under copper stress	Gong et al., 2017

Conclusions

Purpureocillum lilacinum is an endophytic, entomopathogenic microorganism with several important abilities that can be used for various purposes. It can be used for nematode and insect control, as well as a biofertilizer to make nutrients available to plants in the soil. Additionally, it can be used for phytopathogenic control to reduce the presence of pathogens and subsequently decrease the incidence of diseases. By harnessing these diverse skills, *P. lilacinum* presents promising applications in biotechnology and agriculture. Its use can help reduce the dependency on chemical fertilizers, pesticides, and nematicides and contribute to sustainable production practices.

Future Perspectives

As mentioned, the fungus *Purpureocillum lilacinum* presents many different skills, and many of them may be used for biotechnological and agricultural purposes. However, some gaps need to be solved, and information should be generated. Could this fungus make nitrogen available, releasing the nitrogen and phosphorus tapped in the organic matter? Could this fungus make the available phosphorus by solubilizing different sources of unavailable phosphorus? Which insects could be controlled by inoculating this fungus? Could this fungus be used to reduce production costs by reducing the use of chemical fertilizers and pesticides without reducing productivity? These are some gaps that more research needs to answer to make this fungus available to farmers.

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References

1. Backer, R.; Rokem, J.S.; Ilangumaran, G.; Lamont, J.; Praslickova, D.; Ricci, E.; Subramanian, S.; Smith, D.L. Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in plant science* **2018**, *9*, 1473.
2. Ahmad, M.; Pataczek, L.; Hilger, T.H.; Zahir, Z.A.; Hussain, A.; Rasche, F.; Schafleitner, R.; Solberg, S.Ø. Perspectives of microbial inoculation for sustainable development and environmental management. *Frontiers in microbiology* **2018**, *9*, 2992.
3. Moreno-Salazar, R.; Sánchez-García, I.; Chan-Cupul, W.; Ruiz-Sánchez, E.; Hernández-Ortega, H.A.; Pineda-Lucatero, J.; Figueroa-Chávez, D. Plant growth, foliar nutritional content and fruit yield of Capsicum chinense biofertilized with Purpureocillium lilacinum under greenhouse conditions. *Scientia Horticulturae* **2020**, *261*, 108950.
4. Alves, G.S.; Bertini, S.C.B.; Barbosa, B.B.; Pimentel, J.P.; Junior, V.A.R.; de Oliveira Mendes, G.; Azevedo, L.C.B. Fungal endophytes inoculation improves soil nutrient availability, arbuscular mycorrhizal colonization and common bean growth. *Rhizosphere* **2021**, *18*, 100330.

5. Dahlin, P.; Eder, R.; Consoli, E.; Krauss, J.; Kiewnick, S. Integrated control of Meloidogyne incognita in tomatoes using fluopyram and Purpureocillium lilacinum strain 251. *Crop Protection* **2019**, *124*, 104874.
6. Lopez, D.C.; Sword, G.A. The endophytic fungal entomopathogens Beauveria bassiana and Purpureocillium lilacinum enhance the growth of cultivated cotton (Gossypium hirsutum) and negatively affect survival of the cotton bollworm (Helicoverpa zea). *Biological Control* **2015**, *89*, 53-60.
7. Chen, W.; Hu, Q. Secondary metabolites of Purpureocillium lilacinum. *Molecules* **2021**, *27*, 18.
8. Spina, F.; Tummino, M.L.; Poli, A.; Prigione, V.; Ilieva, V.; Cocconcelli, P.; Puglisi, E.; Bracco, P.; Zanetti, M.; Varese, G.C. Low density polyethylene degradation by filamentous fungi. *Environmental Pollution* **2021**, *274*, 116548.
9. Baron, N.C.; de Souza Pollo, A.; Rigobelo, E.C. Purpureocillium lilacinum and Metarhizium marquandii as plant growth-promoting fungi. *PeerJ* **2020**, *8*, e9005.
10. Messa, V.R.; da Costa, A.C.T.; Kuhn, O.J.; Stroze, C.T. Nematophagous and endomycorrhizal fungi in the control of Meloidogyne incognita in soybean. *Rhizosphere* **2020**, *15*, 100222.
11. Nagachandrabose, S. Management of potato cyst nematodes using liquid bioformulations of Pseudomonas fluorescens, Purpureocillium lilacinum and Trichoderma viride. *Potato Research* **2020**, *63*, 479-496.
12. Barbosa, B.B.; Pimentel, J.P.; Rodovalho, N.S.; Bertini, S.C.B.; Kumar, A.; Ferreira, L.F.R.; Azevedo, L.C.B. Ascomycetous isolates promote soil biological and nutritional attributes in corn and soybeans in sandy and clayey soils. *Rhizosphere* **2022**, *24*, 100625.
13. El-Ashry, R.; Ali, M.A.; Elsobki, A.E.; Aioub, A.A. Integrated management of Meloidogyne incognita on tomato using combinations of abamectin, Purpureocillium lilacinum, rhizobacteria, and botanicals compared with nematicide. *Egyptian Journal of Biological Pest Control* **2021**, *31*, 1-10.
14. Giné, A.; Sorribas, F.J. Effect of plant resistance and BioAct WG (Purpureocillium lilacinum strain 251) on Meloidogyne incognita in a tomato–cucumber rotation in a greenhouse. *Pest management science* **2017**, *73*, 880-887.
15. Girardi, N.S.; Sosa, A.L.; Etcheverry, M.G.; Passone, M.A. In vitro characterization bioassays of the nematophagous fungus Purpureocillium lilacinum: Evaluation on growth, extracellular enzymes, mycotoxins and survival in the surrounding agroecosystem of tomato. *Fungal Biology* **2022**, *126*, 300-307.
16. Sharma, A.; Sharma, S.; Sabir, N.; El-Sheikh, M.A.; Alyemeni, M. Impact assessment of Karanja deoiled cake and sundried biogas slurry as a mixed substrate on the nematicidal potential of Purpureocillium lilacinum. *Journal of King Saud University-Science* **2021**, *33*, 101399.
17. Silva, D.M.; de Souza, V.H.M.; Moral, R.d.A.; Delalibera Júnior, I.; Mascarin, G.M. Production of Purpureocillium lilacinum and Pochonia chlamydosporia by Submerged Liquid Fermentation and Bioactivity against Tetranychus urticae and Heterodera glycines through Seed Inoculation. *Journal of Fungi* **2022**, *8*, 511.
18. Chapman, M.A. Introduction: The importance of eggplant. *The Eggplant Genome* **2019**, 1-10.
19. Khan, M.; Tanaka, K. Purpureocillium lilacinum for plant growth promotion and biocontrol against root-knot nematodes infecting eggplant. *Plos one* **2023**, *18*, e0283550.
20. Hossain, M. World pineapple production: An overview. *African Journal of Food, Agriculture, Nutrition and Development* **2016**, *16*, 11443-11456.
21. Kiriga, A.W.; Haukeland, S.; Kariuki, G.M.; Coyne, D.L.; Beek, N.V. Effect of Trichoderma spp. and Purpureocillium lilacinum on Meloidogyne javanica in commercial pineapple production in Kenya. *Biological Control* **2018**, *119*, 27-32.
22. Pagano, M.C.; Miransari, M. The importance of soybean production worldwide. In *Abiotic and biotic stresses in soybean production*; Elsevier: 2016; pp. 1-26.
23. Khush, G. Productivity improvements in rice. *Nutrition reviews* **2003**, *61*, S114-S116.
24. Haque, Z.; Khan, M.R.; Ahamad, F. Relative antagonistic potential of some rhizosphere biocontrol agents for the management of rice root-knot nematode, Meloidogyne graminicola. *Biological control* **2018**, *126*, 109-116.
25. Hernandez-Trejo, A.; Estrada-Drouaillet, B.; Lopez-Santillan, J.A.; Rios-Velasco, C.; Rodríguez-Herrera, R.; Osorio-Hernández, E. Effects of native entomopathogenic fungal strains and neem extract on Spodoptera frugiperda on Maize. *Southwestern entomologist* **2019**, *44*, 117-124.
26. Castillo Lopez, D.; Zhu-Salzman, K.; Ek-Ramos, M.J.; Sword, G.A. The entomopathogenic fungal endophytes Purpureocillium lilacinum (formerly Paecilomyces lilacinus) and Beauveria bassiana negatively affect cotton aphid reproduction under both greenhouse and field conditions. *PloS one* **2014**, *9*, e103891.
27. Hotaka, D.; Amnuaykanjanasin, A.; Maketon, C.; Siritutsoontorn, S.; Maketon, M. Efficacy of Purpureocillium lilacinum CKPL-053 in controlling Thrips palmi (Thysanoptera: Thripidae) in orchid farms in Thailand. *Applied Entomology and Zoology* **2015**, *50*, 317-329.
28. Vitale, J. Economic importance of cotton in Burkina Faso. *Food and Agriculture Organisation, Rome, Italy. Retrieved April* **2018**, *20*, 2018.

 doi:10.20944/preprints202305.1926.v1

29. Rodrigues, J.; Bergamini, C.; Montalva, C.; Humber, R.A.; Luz, C. Simple method to detect and to isolate entomopathogenic fungi (Hypocreales) from mosquito larvae. *Journal of Invertebrate Pathology* **2021**, *182*, 107581.
30. Goffré, D.; Folgarait, P.J. Purpureocillium lilacinum, potential agent for biological control of the leaf-cutting ant Acromyrmex lundii. *Journal of Invertebrate Pathology* **2015**, *130*, 107-115.
31. Desoky, S.M.A.; Abdelall, M.F.; Ahmed, Y. Isolation, Identification, Evaluation of Purpureocillium Lilacinum Egyptian Isolate Toxicity Test in Vitro and Analysis Its Bioactive Products. *Journal of the Advances in Agricultural Researches* **2022**, *27*, 602-617.
32. Bali, G.K.; Singh, S.K.; Maurya, D.K.; Wani, F.J.; Pandit, R.S. Morphological and molecular identification of the entomopathogenic fungus Purpureocillium lilacinum and its virulence against Tuta absoluta (Meyrick)(Lepidoptera: Gelechiidae) larvae and pupae. *Egyptian Journal of Biological Pest Control* **2022**, *32*, 86.
33. Rodriguez, R.; White Jr, J.; Arnold, A.; Redman, a.R.a. Fungal endophytes: diversity and functional roles. *New phytologist* **2009**, *182*, 314-330.
34. Wang, G.; Liu, Z.; Lin, R.; Li, E.; Mao, Z.; Ling, J.; Yang, Y.; Yin, W.-B.; Xie, B. Biosynthesis of antibiotic leucinostatins in bio-control fungus Purpureocillium lilacinum and their inhibition on Phytophthora revealed by genome mining. *PLoS pathogens* **2016**, *12*, e1005685.
35. Sun, Y.; Wu, H.; Zhou, W.; Yuan, Z.; Hao, J.; Liu, X.; Han, L. Effects of indole derivatives from Purpureocillium lilacinum in controlling tobacco mosaic virus. *Pesticide Biochemistry and Physiology* **2022**, *183*, 105077.
36. Barra, P.; Nesci, A.; Etcheverry, M. In vitro compatibility of natural and food grade fungicide and insecticide substances with Purpureocillium lilacinum and their effect against Aspergillus flavus. *Journal of stored products research* **2013**, *54*, 67-73.
37. Yang, S.; Zhang, J.; Liu, Y.; Feng, W. Biodegradation of hydrocarbons by Purpureocillium lilacinum and Penicillium chrysogenum from heavy oil sludge and their potential for bioremediation of contaminated soils. *International Biodeterioration & Biodegradation* **2023**, *178*, 105566.
38. Gong, B.; Liu, G.; Liao, R.; Song, J.; Zhang, H. Endophytic fungus Purpureocillium sp. A5 protect mangrove plant Kandelia candel under copper stress. *Brazilian journal of microbiology* **2017**, *48*, 530-536.
39. Zhan, J.; Qin, Y.; Gao, K.; Fan, Z.; Wang, L.; Xing, R.; Liu, S.; Li, P. Efficacy of a chitin-based water-soluble derivative in inducing Purpureocillium lilacinum against nematode disease (Meloidogyne incognita). *International Journal of Molecular Sciences* **2021**, *22*, 6870.
40. Elsherbiny, E.; Taher, M.; Abd El-Aziz, M.; Mohamed, S. Action mechanisms and biocontrol of Purpureocillium lilacinum against green mould caused by Penicillium digitatum in orange fruit. *Journal of Applied Microbiology* **2021**, *131*, 1378-1390.