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CURRENT STATUS OF PEACH LEAF CURL DISEASE IN PAKISTAN AND FUTURE MANAGEMENT STRATEGIES

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ABSTRACT

Peach leaf curl disease (PLCuD) is a devastating fungal disease that poses a significant threat to peach production globally, and its impact is also evident in Pakistan's fruit industry. The disease is caused by phyto-parasitic fungi from the *Taphrinaceae* family, primarily the genus *Taphrina*. Chemical fungicides are the most common method for controlling the disease; however, their use presents health and environmental concerns and can lead to resistance over time. As a result, alternative control strategies that are both cost-effective and environmentally friendly are essential. Unfortunately, there is a significant gap in knowledge about PLCuD in Pakistan, and the actual cause of the disease remains unidentified, making management impossible. Therefore, discovering novel biological control methods is crucial to combat this disease effectively. Recent advances in biotechnology have shown promising results in developing biological control agents, such as microbial inoculants, bio-fungicides, and bio-pesticides. These agents can specifically target the fungi responsible for the disease, leading to more efficient and sustainable control measures. The review highlights the urgent need to develop sustainable and effective biological control methods to combat PLCuD in Pakistan and to provide innovative and eco-friendly solutions for managing this devastating disease and ensuring the long-term sustainability of the peach industry in Pakistan.

Keywords: Peach, Biotic Constraint, Fungicides, Biological Control, *Taphrina*

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1. INTRODUCTION

Peach (*Prunus persica*) is a diploid model species belonging to the family *Rosaceae* and is widely grown in temperate regions worldwide (Shulaev et al. 2008; Yamamoto and Terakam 2016). Peach is one of the most genetically characterized deciduous trees, with its complete genome sequenced (Verde et al. 2013; Akagi et al. 2016). Peaches, following pear and apple, is the third most economically important fruit (Arús et al. 2012). Known for its distinct velvety skin and juicy, delicious flavor, it is a rich source of fiber, potassium, vitamin A, and vitamin C, making it a nutritious and healthy addition to one's diet. Globally, peach production amounts to approximately 21.6 million tons annually, with China being the major producer, accounting for 54% of the total world production (Memon et al. 2015).

Peach and nectarine trees are susceptible to various fungal pathogens that can infect different parts of the plant, such as the blossoms, foliage, fruit, branches, trunks, and roots (Goldy et al. 2017). Among these pathogens, *Taphrina deformans* is the primary cause of leaf curl disease in peach trees (Pecknold and Paul 2015). Although PLCuD is caused by *T. deformans* (Berk.) is widespread in peach-growing regions globally, it is yet to be confirmed as the causal agent of PLCuD in Pakistan (Sharma et al. 1987). The disease incurs an estimated annual loss of $3 million in the USA and affects 60 to 90% of shoots in Italy, posing a significant threat to peach trees (Rossi et al. 2015). The symptoms of peach leaf curl disease vary depending on the infected plant organ. In the case of young developing leaves, yellow to reddish spots appear in spring, which gradually thicken and pucker. This causes the leaf to curl, leading to stunted growth and reduced yield (Giosuè et al. 2000; Khabazi et al. 2019; Rhouma et al. 2021; Umurzakovich 2022).

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Fungicides are commonly used to target fungi and control plant diseases. However, using fungicides is expensive, unsustainable, and environmentally harmful (Zhang et al. 2015). Moreover, continuous exposure to fungicides may lead to the development of resistance in fungi, rendering the fungicides ineffective (Zhang et al. 2015). As a result, alternative control strategies for PLCuD that are safer, cheaper, environmentally friendly, and effective need to be developed. Alternative approaches could involve the use of natural plant extracts, endophytic bacteria, nanoparticles, selection of disease-resistant peach cultivars, or genetically engineered disease-resistant peach varieties (Mmbaga et al. 2008; Alamri et al. 2012; Alvarez et al. 2012; García-Gutiérrez et al. 2013; Gao et al. 2015; Ali et al. 2016; Chen et al. 2016; Shrestha et al. 2016; Tariq et al. 2022). This review aims to shed light on the current status of PLCuD in Pakistan and propose management and control strategies to eradicate the disease.

1. Peach Production in Pakistan

Peach is a highly popular fruit in Pakistan, second only to apple in popularity. The country has an approximate area of 16,000 hectares dedicated to peach cultivation, with an annual production of 60,000-70,000 tons (Fruit statistics of Pakistan, 2017-2018). Among the stone fruits grown in Pakistan, apricot is the only fruit with higher production than peach. Peach is suitable for cultivation in most parts of Pakistan, except for Sindh province (Table 1). The largest peach-producing province in Pakistan is Khyber Pakhtunkhwa (KP), where it is grown on around 6,000 hectares of land with an average annual production of 35,000 tons (Ahmed et al. 2018). While peach is cultivated in a larger area in Balochistan province, KP has a higher average annual production of peach. Peach cultivation covers around 19% of fruit land in KP. The production of peaches in each province of Pakistan from 2000-2021 is given in Table 2. While peach is cultivated in several districts of KP, District Swat is the most suitable area for peach production. The higher and dominant share of District Swat in terms of area and average annual production of peaches is shown in Table 3. Swat is a hilly area with an altitude ranging from 600 meters to more than 10000 meters above sea level. Due to varied altitudinal gradients and climatic environments, the area harbors rich peach cultivars. However, these cultivars are susceptible to PLCuD, which can lead to epidemics under favorable conditions. Globally, there are more than 3,000 peach cultivars exhibiting significant phenotypic diversity, resulting in fruits with various flavors, textures, and sweetness-to-acidity ratios (Monti et al. 2016). At least 20 peach cultivars are grown in Pakistan, each with its local name in the market. The most popular cultivars in Pakistan include Early Grand, Arctic Fantacy, Florida King 6-A, Florida King 8-A, Golden Early, Texas y-455, Micholea, Shah Pasand, Spring Creast, Swanee, Shireen, and A669, among others.

Table 1: Area under peach cultivation in each province of Pakistan

Years	Ares ('000' Hectares) wise peach production in each province of Pakistan				Total area
	Punjab	Sindh	KP	Baluchistan	Pakistan
2010-2011	68	-	5550	9478	15096
2011-12	42	-	5929	9442	15409
2012-2013	37	-	6329	7650	14016
2013-2014	39	-	6330	7655	14024

Ministry of National Food Security and Research, Government of Pakistan.

2. Peach Leaf Curl Disease (PLCuD) and the Life Cycle of *Taphrina* Species

PLCuD is a fungal disease of global economic importance that mainly affects the leaves of peaches, nectarines, and sometimes other stone fruits such as apricots and almonds (Frisullo et al. 2000; Rossi et al. 2007; Cissé et al. 2013;). The disease is caused by at least four distinct species of the genus *Taphrina*. It has approximately 28 species, but *T. deformans* is the most prominent and widespread species of the genus (Pecknold and Paul 2015).

Fungicide tests and inoculation experiments have demonstrated that the fungi involved in PLCuD is monocyclic, meaning that the disease develops each spring from overwintered yeast cells on peach buds (Pierce, 1900; Fitzpatrick, 1934; Mix, 1935; Caporali, 1964). *T. deformans* has a dimorphic life cycle with two phases: the parasitic mycelium and the saprobic yeast phase (Fonseca and Rodrigues, 2011). The yeast phase of the dimorphic ascomycete starts when ascospores discharged from curled leaf bud onto peach bud and twig surfaces (Pscheidt, 1995; Bacigálová et al. 2003; Tavares et al. 2004). The fungus switches to the parasitic mycelial stage under favorable climatic conditions when overwintered yeast cells, also known as bud-conidia, come into contact with young leaves (Tavares et al. 2004). The typical curl symptoms on leaves appear throughout the early summer and spring during the mycelial stage, which is easily recognized (Fonseca and Rodrigues 2011).

The mycelial cells of *T. deformans* comprise two nuclei that can grow into an ascus that contains eight uninucleated ascospores. These ascospores can multiply by budding inside or outside the ascus, producing small, round, or ovoid conidia (blastospores) that are haploid and uninucleate. These blastospores can germinate to produce mycelium or bud again to create more thin or thick-walled blastospores. When the conidia germinate, the nucleus divides, and two nuclei enter the germ tube. As the mycelium grows, both nuclei divide simultaneously, generating the binucleate cells that make up the mycelium (Agrios 1978).

Table 2: Peach production in each province of Pakistan from 1999-2000 to 2016-17

Years	Peach production in each province of Pakistan (Production '000' Tones)				Total production
	Punjab	Sindh	KP	Baluchistan	Pakistan
1999-2000	1.20	0.00	14.50	17.30	33.00
2000-01	1.20	0.00	14.80	16.90	32.90
2001-02	1.16	0.00	20.96	15.40	37.52
2002-03	1.15	0.00	60.20	15.03	76.38
2003-04	0.90	0.00	56.76	18.56	76.22
2004-05	0.50	0.00	50.94	18.15	69.59
2005-06	0.50	0.00	51.59	18.23	70.32
2006-07	0.42	0.00	53.11	17.73	71.26
2007-08	0.42	0.00	56.64	25.33	82.39
2008-09	0.47	0.00	57.83	25.36	83.67
2009-10	0.40	0.00	32.30	21.30	54.00
2010-11	0.40	0.00	30.80	21.40	52.60
2011-12	0.20	0.00	33.30	20.80	54.30
2012-13	0.20	0.00	36.10	19.30	55.60
2013-14	0.20	0.00	41.40	19.30	60.90
2014-15	0.20	0.00	48.10	18.10	66.40
2015-16	0.20	0.00	52.01	18.54	70.75
2016-17	0.23	0.00	54.55	16.86	71.64
2017-18	0.20	0.00	56.80	16.90	73.90
2018-19	0.38	0.00	71.58	15.91	87.86
2019-20	0.40	0.00	73.20	37.30	110.90
2020-21	1.89	0.00	69.42	39.46	110.76

Agricultural statistics of Pakistan. http://www.amis.pk/Agristatistics/Data/HTML%20Final/Peach/Production.html

Table 3: Districts-wise production of peaches in various districts of Khyber Pakhtunkhwa (2010-2011)

Parameters	Swat	Mardan	Haripur	Buner	Upper Dir	Peshawar	Nowshehra
Cultivated area	9263	924	924	272	245	200	185
Production	17625	3617	1018	1066	891	930	750

Area is represented in hectares, while production is in tons (Khan et al. 2014).

Despite extensive research, how *T. deformans* survive from one season to the next is still unclear. While it was once thought that the perennial mycelium survived in shoots over the winter and infected new leaves in the spring, this theory has been refuted by several researchers. There is no evidence that *T. deformans* mycelium survives in twigs beyond the current season or that it spreads from a diseased twig into a new foliage shoot (Mix 1935). Secondary spores grown in culture can survive through the winter on peach shoots and cause spring infections. However, efforts to isolate spores that occur naturally on dormant trees have yielded largely unsuccessful results (Atkinson 1968). There is no evidence that the fungus overwinters in severely infected leaves (Booth 1998).

Taphrina deformans can infect most peach cultivars that have been identified (Tavares et al. 2004). *Taphrina* passes through the stomata to enter the host cells (Goldy et al., 2017). Peach leaves afflicted by the disease will curl and exhibit a discoloration that can appear as either reddish or pale green (Fonseca & Rodrigues., 2011). These modifications in the leaves generally occur because of the indole acetic acid produced by the fungus (Cissé et al., 2013). However, such alterations are commonly observed to be limited to certain portions of the leaf rather than affecting the entire leaf (Caporali 1964). These changes indicate structural changes in the leaf, with the palisade layer becoming indistinguishable from the spongy mesophyll (Matuyama and Misawa 1962; Marte and Gargiulo 1972; Moscatello et al. 2017). During the infection, alterations in the anatomy of the host cells have also been observed (Giordani et al. 2013). Changes in the plant cell wall at its fungal interface, invaginations of plasmalemma and tonoplast, and an increase in the number of plasmodesmata are some of the modifications observed during infection. Additionally, the chloroplasts are reduced in size and contain fewer grana. Infected leaves also show altered metabolism and physiology, with increased transpiration and reduced photosynthesis (Raggi 1967; Raggi 1995; Moscatello et al. 2017). Green shoots can also get infected, becoming thickened and distorted. Infections of the fruit are less common, and the resulting lesions are reddish, irregular, and wrinkled (Giosuè et al. 2000; Koleva-Valkova et al. 2017; Rossi et al. 2007).

Extended periods of wet and cold weather during bud development can significantly increase the likelihood of severe outbreaks of leaf curl. Long rainy seasons favor serious orchard-level outbreaks, although it has been shown that the fungus can start to grow at 95% relative humidity. Cold temperatures favor the development of the leaf curl, and the fungal growth temperature ranges from 6 to 26°C, with optimal growth at 18–20°C. Disease incidence depends on the inoculum density in the orchard, cultivar susceptibility, and meteorological conditions influencing overwintering and infection (Giosuè et al. 2000; Rossi et al. 2007; Goldy et al. 2017).

2.1 Peach Leaf Curl Disease in Pakistan

Peach leaf curl disease is one of the significant constraints for peach production in Pakistan's peach-growing areas. Though the disease is much alarming in Pakistan, it still remains unnoticed. To our knowledge, there is no published data on PLCuD from Pakistan; therefore, no serious attention has been given to eradicating this devastating disease in the country. It is still unclear which fungal pathogen(s) may be involved in the disease. However, it is hypothesized that *T. deformans* may be the actual causative agent for the disease. Alternatively, the possibility of mixed infection could also exist. Currently, there are no estimates for the loss assessments of this disease in Pakistan. The disease symptoms observed in peach cultivars grown in Pakistan (Fig. 1) are similar to the PLCuD caused by *T. deformans* in other countries (Watt 2010; Adaskaveg et al. 2012; Pecknold and Paul 2015). Currently, our research group has cultured the fungi on potato dextrose agar (PDA) media from the leaves and buds of the peach plant. The cultured fungi had the characteristic morphological features of *T. deformans*. Interestingly, three morphologically distinct colonies were isolated, suggesting the possibility of more fungal species/ strains in the disease (A. Rahman, F. Akbar, unpublished results). The ITS region was subjected to molecular characterization, and the analysis revealed that the obtained sequences shared a 99% sequence similarity with *T. deformans* (A. Rahman, F. Akbar, unpublished results). Moreover, it was found that a few of the sequences obtained show similarity to uncultured fungi as well as other fungi, namely *Cryptococcus adeliensis* and *Naganishia uzbekistanensis* (A. Rahman, F. Akbar, unpublished results). *Cryptococcus adeliensis* has previously been isolated from stone fruit trees, including peach trees, in Iran (Borhani and Rahimian 2016). This research indicates that various fungal species may play a role in causing PLCuD in Pakistan in addition to the primary infection caused by *T. deformans*. However, further studies would be needed to confirm these preliminary observations and to test Koch's postulates. Though PLCuD has caused significant damage to Pakistan's fruit industry, none seriously addressed the problem. Therefore, this is crucial to identify the causative agents involved in the disease and to find long-term, cost-effective, and safe measures to control and eradicate this disease.

3. Management and Control Strategies for PLCuD

Estimating crop losses due to diseases can be challenging, and different methods may produce varying levels of accuracy. However, regardless of the accuracy level, it is clear that disease management strategies are necessary to minimize losses. To develop effective short- and long-term management plans, three approaches are commonly employed: exclusion, eradication, and immunization. Efficient management of crop diseases depends on the

Fig. 1: Typical disease symptoms of peach leaf curl disease in Pakistan.

accurate and timely identification of microbial plant pathogens and the precise diagnosis of diseases in infected crops caused by such pathogens (Narayanasamy 2002). There are no management options after the infection has occurred. A single application of fungicides can achieve control in the fall after 90% of leaves have fallen to the ground (Steiner and Biggs 2010). Further research would be needed to formulate novel control methods for eradicating PLCuD.

4.1. Control of PLCuD by Chemical Fungicides

Single fungicide application can effectively manage the disease when administered either prior to bud swell in spring or following the general leaf fall in autumn. To control peach leaf curl, recommended fungicides include copper oxychloride, carbendazim, or lime sulfur. Additional fungicides that have been shown to be effective against the disease include Chlorothalonil, Captan, Dodine, Thiram, Captafal, and Ziram (Ram and Bhardwa 2004; Pecknold and Paul 2015).

Peach leaf curl can become a severe disease on unsprayed trees. Improper timing of fungicide application and inadequate spray coverage are common causes of failure in controlling fungal infections (Tate et al. 1987). While a single well-timed fungicide spray in early spring can usually control the disease, in reality, even multiple sprays from leaf fall to early blossom may not completely prevent leaf curl in all terminal shoots (Fitzpatrick 1934). Fungicides control peach leaf curl by targeting and eliminating fungal spores on trees, especially those that have germinated. The primary objective is to have enough chemicals on the plants to wash away some of the fungi between the bud scales and eliminate any spores that may be present there (Heyns 1965). Unfortunately, no chemical fungicide yet discovered can control fungi once the fungus has entered the leaves, so treatments must be implemented before leaves arise.

While synthetic fungicides have successfully protected crops from fungal infections, the rise of fungal resistance to these chemicals is becoming an increasingly serious issue (Zhang et al. 2015). Synthetic fungicides have drawbacks in that they can be non-biodegradable and accumulate in the soil, crops, and water, potentially causing harm to humans through the food chain. Additionally, most of these chemical fungicides are known to be neurotoxic and carcinogenic (Mdee et al. 2009). Adverse effects of lime sulfur on humans, especially respiratory tract, eyes, and skin have been documented (Gammon et al. 2010). Furthermore, there have been reports of strains of *T. deformans* developing resistance to copper fungicides, which can reduce the effectiveness of this control method over time (Cissé et al. 2013; Win et al. 2020). Due to the potential harm that chemical fungicides can cause to both human health and the environment, there is a growing need to find alternative and sustainable methods for controlling plant diseases (Hostettmann et al. 2000; Alamri et al. 2012; Mohamed et al. 2021; Kumar et al. 2022).

4.2. Control of PLCuD by Resistant Peach Cultivars

The majority of the peach cultivars are susceptible to the PLCuD. However, a few peach varieties/ cultivars are available that are tolerant or partially resistant to leaf curl. The partial resistant cultivars include Frost, Indian Free, Redhaven, Muir, Q-1-8, Favorita, Morettinijaune Gold, Fertilia-1, Eixan-1, Modeline Pouyet, Flacara X HB9-35, Flacara X Miorita, J.H. Hale X Sunbeam Stark Early Giant, Starking Delicious, World Earliest and Tesia Samisto, etc. (Coroianee and Ivascu 1981; Ritchie and Werner 1981; Nautiyal et al. 1988). The tolerant cultivars include World's Earliest, July Alberta, and Bed Will's Early (Ram and Bhardwaj 2004). The Frost is much more tolerant to fungi, but it must receive fungicide applications in the first 2 to 3 years. Redhaven and its cultivars have been observed to exhibit tolerance to PLCuD, whereas Redskin and cultivars derived from it show varying levels of susceptibility to the disease, ranging from less susceptible to highly susceptible (Curl., 2012). Vol'vach (1986) observed that some varieties, such as Early Red, Nectared 2, Stark Redgold, Sunhaven, Nectared4, Springtime, and Early Redhaven, exhibited high resistance to PLCuD under conditions of severe natural infection in the Crimea. Thus, screening all the available peach cultivars against the PLCuD is important to find the most suitable resistant cultivars for future recommendations to the farmers. Studies suggest that late-blooming peach cultivars may have less susceptibility to peach leaf curl disease than early blooming cultivars. This is because late-blooming cultivars may avoid the cool and wet weather conditions that are ideal for disease infection, unlike early blooming cultivars that are more likely to experience such conditions during the bud development phase (Ritchie and Werner 1981). While bloom time is thought to be a contributing factor to susceptibility to peach leaf curl, other factors may also play a role. For example, a study by Ritchie and Werner (1981) found that some peach cultivars with similar bloom times exhibited different levels of susceptibility to the disease, suggesting that genetic differences among cultivars may also play a role. Additionally, environmental factors such as temperature, humidity, and rainfall can influence the severity of the disease, regardless of bloom time or cultivar susceptibility.

4.3. Control of PLCuD Using Plant Extracts as Antifungal Agents

Plants possess the ability to produce secondary metabolites as a defense mechanism against fungal infections, which exhibit antifungal activity. Many plant species have been found to contain significant amounts of these antifungal agents (Eloff and McGaw 2014; Raut and Karuppayil 2014). Using plant extracts that possess inhibitory activity against fungal pathogens may provide a promising solution for developing eco-friendly and sustainable fungicides (Athukoralage et al. 2001). These products have a specific mode of action and a narrow target range. In addition, plant extracts have the advantage of containing a mixture of compounds that can work together synergistically to inhibit the growth of phytopathogenic fungi. Many plant extracts generally have more than one antifungal compound (Masoko and Eloff 2005). Thus, plant extracts are ideal for targeted use, have minimal effects on beneficial microorganisms, degrade rapidly in the field, and have a shorter shelf life with no residual risks. *Citrus paradisi*, commonly known as grapefruit, contains the naturally occurring compound 7-geranoxy coumarin, which has been shown to exhibit potent antifungal activity against *Penicillium italicum* and *P. digitatum* both *in vitro* and *in vivo*. Several plant phenolic compounds (resorcinol, phenol, pyrocatechol, pyrogallol, and chlorogenic acid) exhibit inhibitory effects against *Botryodiplodia theobroma*, a fungal pathogen that causes Java black rot in sweet potato. *Acacia nilotica* contains the natural compound kaempferol, which has been found to possess antifungal activity against *P. italicum*, a fungal pathogen responsible for causing post-harvest rot in citrus fruits. Gurib-Fakim (2006) reported that lawsone, which is extracted from the Henna plant (*Lawsonia inermis*), exhibits strong fungicidal properties. Two compounds eleutherinone and naphthaquinones extracted from *Eleutherine bulbosa* also have antifungal activity. Zrumbone and Sesquiterpene have antifungal activity against *Rhizoctonia solani* (Okwute 2012). Solvent–solvent fractionation of *Melianthus comosus* acetone leaf extracts resulted in a product with a more significant *in vitro* activity against certain fungi than the tested commercial fungicides (Cowan 1999; Ribera and Zuñiga 2012). Currently, we have tested two plant extracts against the fungi isolated from the infected peach plant. Both plant extracts showed remarkable fungicide activities against all the fungal species/ strains isolated from the peach plant (D. Khan, F. Akbar, unpublished results). Seaweed extracts have also been shown to enhance resistance to certain pests and pathogens (Atkinson 1968; Castle 1984; Chase 1948a; Chase 1948b). According to Castle (1984), applying seaweed extracts has been observed to make peach trees resistant to peach leaf curl. Therefore, it is suggested to test the seaweed extracts and other suitable plant extracts with antifungal activity against the causative agents of PLCuD. The bioactive compounds of *Chaetomium* species have shown excellent antifungal activity against several phytopathogens (Soytong 2001; Soytong 2014). *Chaetomium* species are recorded to have antagonistic effects on many phytopathogens such as *Phytophora palmivora* (Hung et al. 2015). *P. oryzae* (Soytong 1989), *Fusarium oxysporum*, and *Colletotrichum gloeosporioides* (Soytong 2001; Song et al. 2018).

4.4. Control of PLCuD by Nanoparticles

Nanotechnology is a multipurpose discipline that has gained tremendous applications in many fields of science (Beyth et al. 2015). Nanoparticles (NPs) have a size range between 1 and 100 nanometers and are made up of organic matter, carbon, metal, or metal oxides (Ealias and Saravanakumar 2017). These particles provide high activity in a minimal dose. The large surface area of nanoparticles relative to their size makes them strategically advantageous as active antimicrobial groups (Beyth et al. 2015; Zhang et al. 2010; Kale et al. 2021). Different nanoparticles have been used for their antimicrobial efficacy. Nanoparticles (NPs) have been found to exhibit antifungal activity through two main mechanisms of action: 1) disruption of the pathogen's cell membrane integrity and 2) induction of reactive oxygen species (ROS) overload (Wang and Shao 2017).

The use of silver nanoparticles (AgNPs) in plant disease management has become more common, and new technologies are making its manufacturing more economical. Currently, plants are being used for the green synthesis of NP (Ullah et al. 2018). Silver nanoparticles (AgNPs) have been shown to possess a range of modes of action against plant pathogens, making them a potentially safe and effective alternative to synthetic chemicals for plant disease control (Mendes et al. 2014; Ibrahim et al.2020). AgNPs have excellent antifungal and antibacterial effects. AgNPs have been shown to have a high inhibitory activity against fungi, which may be attributed to their ability to interact with proteins, leading to protein inactivation and directly interacting with DNA, which can result in DNA mutation (Feng et al. 2000). AgNPs are known to be small, allowing them to penetrate through cell walls easily. They can then accumulate in the cell membrane, causing disruptions in its function, ultimately leading to the cell's death. This property of AgNPs makes them effective against plant pathogens. Studies have shown that AgNPs can influence the plasma membrane functions of fungi, leading to their inhibition or death (Kim et al. 2009). AgNPs can accumulate in the cell membrane and cause irregularly shaped pits, leading to membrane permeability and respiratory chain disturbances. Additionally, bound lipids and enzymes can result in the lysis of cells, as observed in studies by Amro et al. (2000) and Elechiguerra et al. (2005). AgNPs work efficiently against the fungal and bacterial pathogens of *Aspergillus flavus*, *A. niger*, *Candida albicans*, *Raoultella planticola*, *Pseudomonas aeruginosa* and *B. subtilis* (Rajeshkumar 2019). The nanoparticles nano-ECL, nano-MCL, and nano-HCL of *C. lucknowense* origin have antifungal activity against *P. oryzae*, which causes rice blast disease (Song et al. 2018). The AgNPs have demonstrated outstanding antimicrobial activity against plant pathogens, i.e., *A. alternate* and *Erwinia carotovora* (Abbas et al. 2019) and could be tested against *T. deformans*. However, using the green synthesized NPs of essential nutrients is suggested, which should provide the dual function of protecting plants from pathogens and providing plants with essential nutrients.

4.5. Control of PLCuD by Endophytic Bacteria

Endophytes are microbes residing within plant tissues without adversely impacting the host plant (Bacon and White 2000). These microorganisms and their metabolites often benefit plant crops by providing host tolerance against biotic and abiotic stresses (Rosenblueth and Martínez-Romero 2006). Some endophytes also protect host plants from insects by producing anti-pest compounds. Microbe communities can be present in many host plant tissues. The application of microorganisms for the control of plant fungal diseases relies on the ability of some microorganisms to inhibit the growth and development of fungal pathogens through various mechanisms such as competition, antibiosis, and induction of plant defense responses. Several endophytic bacteria and fungi have shown antagonism against phytopathogens (Alvarez et al. 2012; Ali et al. 2016; Chen et al. 2016; Shrestha et al. 2016; Mmbaga et al. 2008). For example, *Trichoderma* has shown 100% antagonism against *F. graminearum* and *F. crookwellense* (causing disease in wheat and other cereal crops) (Schöneberg et al. 2015). *Bacillus* species are the most promising candidates as biological control agents against different plant fungal infections. An endophytic *Bacillus subtilis* strain has recently been used as an effective biological control agent against wheat powdery mildew caused by *Blumeria graminis* (Gao et al. 2015). *Bacillus amyloliquefaciens* has been used to control apple ring rot and Sclerotinia stem rot of soybean caused by *Botryosphaeria dothidea* and *Sclerotinia sclerotiorum*, respectively (Alvarez et al. 2012; Chen et al. 2016). *Bacillus subtilis* and its metabolic products have been used to control cucurbit powdery mildew and foliar diseases caused by *Podosphaera fuscaand* and *Alternaria* species, respectively (García-Gutiérrez et al. 2013; Ali et al. 2016). Biological control activity of rice-associated *Bacillus* species has been observed against *Rhizoctonia solani*, which causes sheath blight disease (Shrestha et al. 2016).

An antifungal lipopeptide, Cryptocandin A has been isolated from endophytic *Cryptosporiopsis quercina* bacteria that contain uncommon hydroxylated amino acids and 3 hydroxy-4-hydroxymethyl proline that have been found effective against certain fungal pathogens such as *C. albicans*, *S. sclerotiorum* and *Botrytis cinerea* (Photita et al. 2001). A cryptocin of tetramic acid derived from endophytic microbe, demonstrated powerful activity against pathogenic fungi of the plant *Pyricularia oryzae*. A *Pestalotiopsis microspora* strain, isolated from the *Torreya taxifolia* tree, generates an antifungal compound pestaloside. The antibiosis mechanism involves the development of bioactive organic volatile compounds (VOCs), antibiotic compounds, and certain enzymes (Ownley et al. 2010). Compared to other control methods, biological control via endophytic bacteria is very specific, efficient, and less expensive. There is no research on the application of endophytic bacteria as biological control agents for PLCuD. Though, the causative agent of the disease has not yet been identified and characterized. It would be beneficial to search for novel endophytic bacteria/ microorganisms that have antifungal activity against the causative agents of PLCuD.

4.6. Control of PLCuD by Plant Growth-Promoting Rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) can play a significant role in controlling PLCuD. PGPR are free-living soil and rhizosphere bacteria that are beneficial to plant growth. They have been shown to have an antagonistic effect against plant pathogens and can also act as biological control agents. The use of PGPR as a control measure offers several advantages over conventional chemical sprays, such as reduced environmental contamination and the ability to enhance plant growth and productivity (Lugtenberg and Kamilova 2009; Nakkeeran et al. 2005). PGPR occur naturally, are non-toxic and ecologically friendly, and their implementation is sustainable. They have diverse action modes, including producing cell wall degrading enzymes, iderophores, antibiosis, bio-surfactants, and volatiles, and also induce systemic resistance in plants (Labuschagne et al. 2010). Biocontrol refers to the management of diseases in both living plants and fruits during post-harvest. Rhizobacteria are often studied for their potential to control pathogenic microorganisms in plants (Lugtenberg and Kamilova 2009). PGPR can also be genetically engineered to improve biocontrol efficacy (Nakkeeran et al. 2005; Lugtenberg and Kamilova 2009).

Plant growth-promoting bacteria (PGPB) can promote plant growth by inhibiting the growth of phytopathogens through the production and secretion of siderophores, which are molecules that bind to Fe+3 ions in the rhizosphere. By reducing the availability of Fe+3, PGPB can effectively prevent fungal pathogens from proliferating in the immediate vicinity. The siderophores produced by PGPB have a higher affinity for iron than those produced by fungal phytopathogens, which further increases their effectiveness (Pahari and Mishra 2017; Vejan et al. 2016). Studies have shown that *B. amyloliquefaciens* (SN13) has biocontrol capabilities against *R. solani*, by extending tolerance via plant defense responses (Srivastava et al. 2016). When plants are colonized with *B. amyloliquefaciens*, it alters phytohormone signaling, induces production of secondary metabolites, maintains elicitors, and balances ROS production while producing ROS scavengers (Srivastava et al. 2016). Inoculation of *Bacillus* species in cotton plants resulted in increased expression of genes responsible for the synthesis of jasmonates and allelochemicals. This leads to reduced feeding by *Spodoptera exigua* larvae. Additionally, *Enterobacter asburiae* BQ9 induces resistance against plant viruses by increasing the expression of stress-related genes and antioxidant enzymes such as superoxide dismutase, catalase, peroxidase, and phenylalanine ammonia-lyase (Zebelo et al. 2016; Li et al. 2016; El Gamal et al. 2022). Bacteria that produce beta-glucanases and chitinases can be used to inhibit fungal growth since the major components of the fungal cell wall are beta-glucan and chitin. The *P. fluorescens* KCC5 and *Sinorhizobium fredii* produce beta-glucanases and chitinases and have been tested as biocontrol agents against the Fusarium wilt produced by *Fusarium udum* (Kumar et al., 2010). The PGPB can also be tested against the causative agents of PLCuD.

4.7. Control of PLCuD by Transgenic Plants

Plant genetic engineering has emerged as a powerful strategy for conferring resistance to fungal pathogens. To achieve this, different methods have been employed, including the high-level expression of antifungal proteins like chitinases, glucanases, and ribosome-inactivating proteins, as well as the production of low molecular weight compounds such as phytoalexins. Many studies have shown that transgenic plants overexpressing the chitinase gene display enhanced resistance to fungal infections, which is likely due to the rapid breakdown of the fungal cell wall chitin. For instance, the overexpression of the chitinase gene in rice has been shown to confer resistance against the sheath blight pathogen, *R. solani* (Kumar et al. 2003). In studies conducted by Saitoh et al. (2001), it was found that defensin peptide isolated from transgenic plants demonstrated antifungal activity against *M. grisea* and *B. cinerea*. In another study, introduction of the gene encoding chickpea defensin peptide, Ca-AFP, into tobacco plants resulted in enhanced resistance to *Alternaria solani* (Islam 2004). However, the application of transgenic methods for enhancing fungal resistance is currently limited to a small number of phytopathogenic fungi such as *Phytophthora infestans*, *Verticillium dahliae*, *A. solani*, and *R. solani*. Since there are approximately 10,000 plant-pathogenic species, more research is necessary to develop resistance against other pathogenic fungi. Fortunately, the genome of *P. persica* has already been sequenced (Ahmad et al. 2011), and it can be genetically engineered to induce resistance to the pathogen that causes PLCuD.

Conclusion: PLCuD has become a serious threat to peach production in Pakistan, and no serious attention has been given to finding the actual causative agent (s) of the disease. Also, the efforts for a stable and long-term solution to the problem are very limited. The application of chemical fungicides on peach plants has become useless despite its severe detrimental impact on human health and the environment. Therefore, alternate safe biological control methods are suggested for managing disease and long-term usage. This should reduce the burden of extensive use of chemicals and environmental pollution and overcome the fungicide resistance problem. However, a more profound insight would be required to understand the exact nature of the causative agents in Pakistan and future comprehensive research to identify novel control methods for eradicating PLCuD.

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Conflict of Interests

The authors declare that they have no competing interests.

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