

POTATO LATE BLIGHT CAUSED BY *PHYTOPHTHORA INFESTANS*: BIOLOGY, EPIDEMIOLOGY, CLIMATE CHANGE, AND SUSTAINABLE MANAGEMENT STRATEGIES

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ABSTRACT: Potato late blight, caused by *Phytophthora infestans*, remains one of the most destructive diseases affecting global potato production, resulting in substantial yield and economic losses. This review summarizes the pathogen's biology, disease cycle, epidemiology, host-pathogen interactions, and current diagnostic approaches, along with major management strategies, including cultural practices, host resistance, biological control, botanical extracts, chemical control, disease forecasting, and integrated disease management. It also highlights the impacts of climate change on disease distribution and severity, as well as recent advances in molecular breeding, genome editing, and precision agriculture. Overall, sustainable management of potato late blight requires integrating resistant cultivars, environmentally friendly control measures, disease forecasting, and judicious fungicide use. Continued research on durable resistance, climate-smart management, and emerging biotechnological tools will be essential to enhance potato resilience and ensure future food security.

KEYWORDS: Potato; *Phytophthora infestans*; Integrated disease management; Host plant resistance; Climate change; Biological control.

INTRODUCTION

Potato plays a vital role in ensuring food security, particularly in developing countries, where it is one of the four major staple crops that collectively provide approximately 50% of the world's dietary energy alongside rice, wheat, and maize (Wijesinha-Bettoni & Mouillé, 2019). It is a nutritionally important crop that contributes significantly to global food and nutritional security (Singh *et al.*, 2020). Potato tubers are rich sources of essential minerals, including potassium, phosphorus, magnesium, sodium, and calcium, as well as vitamins, particularly vitamin C and several B-complex vitamins (Varga & Đurović, 2023). China accounts for

the largest potato cultivation area globally, followed by other major producers such as India. The global potato processing industry was valued at approximately USD 41 billion in 2023 and is projected to exceed USD 60 billion by 2031, reflecting the increasing demand for processed potato products worldwide (Hu *et al.*, 2025). However, potato productivity and tuber quality are severely constrained by numerous insect pests and diseases, among which late blight, caused by *Phytophthora infestans*, is the most destructive, resulting in annual economic losses of billions of dollars worldwide (Chakrabarti *et al.*, 2022).

Late blight, caused by the oomycete *Phytophthora infestans* (Mont.) de Bary, is

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one of the most destructive and extensively studied diseases of potato, capable of causing yield losses of up to 100% under favorable environmental conditions (Mizubuti & Fry, 2006; Tsedaley, 2014; Lal *et al.*, 2018). The disease is historically significant for causing the Irish Potato Famine during the 1840s, which resulted in catastrophic crop failures, widespread famine, a decline of more than 20% in Ireland's population due to starvation, and mass migration (Yoshida *et al.*, 2013; Majeed *et al.*, 2017). More than 175 years later, late blight remains one of the most economically important plant diseases worldwide, with *P. infestans* causing annual losses exceeding US\$10 billion through yield reduction and disease management costs (Lal *et al.*, 2018; Rhouma *et al.*, 2024). Rising global food demand, climate change, the emergence of more virulent pathogen genotypes, and fungicide-resistant populations have intensified the need for sustainable late blight management strategies (Dong & Zhou, 2022; Wang *et al.*, 2025). The pathogen reproduces rapidly through asexual spores under cool and humid conditions because its infection cycle is highly dependent on moisture (Melhus, 1915; Fry, 2008). Under high humidity, *P. infestans* can complete its asexual infection cycle in approximately four days, with cool temperatures (10–15°C) promoting rapid zoospore germination and warmer temperatures (20–25°C) favoring direct germ tube penetration (Fry, 2008).

Effective management of late blight requires an integrated approach that combines resistant cultivars, cultural practices, disease forecasting systems, biological control agents, and judicious fungicide applications (Dong & Zhou, 2022; Bourki *et al.*, 2026). Recent advances in pathogen biology, molecular diagnostics, host resistance breeding, and precision agriculture have further expanded opportunities for developing sustainable and

environmentally sound disease management strategies (Bourki *et al.*, 2026). This review provides a comprehensive overview of potato late blight, covering its causal organism, epidemiology, symptomatology, disease cycle, host–pathogen interactions, diagnostic approaches, and integrated management strategies. It also highlights recent advances, current challenges, and future research directions for achieving sustainable management of this economically important disease.

Causal Organism

Phytophthora infestans is an obligate biotrophic oomycete belonging to the kingdom Stramenopila. Although it is commonly referred to as a fungus because of its filamentous growth habit and disease symptoms, it is phylogenetically distinct from true fungi and is more closely related to brown algae and diatoms (Judelson, 2014). The pathogen produces coenocytic, multinucleate, and predominantly aseptate hyphae, with hyaline, lemon-shaped, papillate sporangia borne singly on the tips of branched sporangiophores. It is heterothallic, requiring two compatible mating types (A1 and A2) for sexual reproduction (Raza *et al.*, 2022; Mugao, 2023).

During its life cycle, *P. infestans* differentiates hyphae into sporangia that facilitate dispersal and host infection through protein kinase-mediated phosphorylation pathways (Judelson & Ah-Fong, 2010). The pathogen reproduces both asexually through sporangia, zoospores, and mycelium and sexually through oospores, enabling survival under diverse environmental conditions (Andrison, 1995). Between cropping seasons, it survives primarily in infected seed tubers, volunteer potato plants, cull piles, and, where both mating types coexist, persistent soil-borne oospores, which serve as the primary

inoculum for new epidemics (Andrivon, 1995; Johnson, 2010; Hu *et al.*, 2022). Under favorable environmental conditions, these survival structures initiate disease outbreaks, with airborne sporangia driving rapid secondary spread and repeated infection cycles (Wang *et al.*, 2025).

The population biology of *P. infestans* is characterized by frequent migration, genetic recombination, and natural selection, resulting in rapid shifts in pathogen populations across time and geographic regions (Fry, 2016). Its genome has evolved through transposable elements, horizontal gene transfer, gene family expansion, and transcriptional and epigenetic regulation, enabling dynamic gene expression during development and host infection (Judelson, 2014). Although potato and tomato are the primary hosts, *P. infestans* can also infect other members of the Solanaceae, including wild species such as *Solanum dulcamara*, *S. sarrachoides*, and petunia, which may act as reservoirs of inoculum between cropping seasons (Leesutthiphonchai *et al.*, 2018).

Infection process

Most *Phytophthora infestans* infections are initiated by asexual sporangia, which germinate either directly or by releasing motile zoospores depending on temperature. At temperatures above 15°C, sporangia germinate directly to infect host tissues, whereas at lower temperatures they release 10–12 motile zoospores that swim in water films, encyst, and initiate infection (Ghorbani *et al.*, 2004). Following encystment, germ tubes penetrate host tissues through appressoria, stomata, wounds, or other natural openings (Leesutthiphonchai *et al.*, 2018). Successful infection is facilitated by the formation of specialized structures, including appressoria, which enable host penetration (Avrova *et al.*, 2008). After penetration, the pathogen

develops intercellular hyphae and haustoria to acquire nutrients from living host cells while secreting effector proteins and small RNAs that suppress plant immune responses and promote colonization (Leesutthiphonchai *et al.*, 2018; Singh *et al.*, 2026). As the infection progresses, new sporangia are produced, host tissues become necrotic, and secondary disease cycles are initiated (Leesutthiphonchai *et al.*, 2018). Between growing seasons, the pathogen survives primarily as mycelium in infected tubers, providing an important source of primary inoculum for subsequent epidemics (Ghorbani *et al.*, 2004).

The pathogenicity of *P. infestans* varies among physiological races because of differences in virulence and gene expression. Highly aggressive strains exhibit rapid mycelial growth and enhanced expression of genes involved in carbon metabolism, amino acid biosynthesis, glycolysis, and cell wall degradation, leading to faster host colonization and disease development (Deng *et al.*, 2025). Sexual reproduction is regulated by coordinated expression of genes associated with epigenetic regulation and RXLR effectors, with Avrblb2 contributing to both virulence and oospore formation (Tzelepis *et al.*, 2020).

Potato responds to *P. infestans* infection by activating multiple defense mechanisms. During incompatible interactions, rapid oxidative and nitrosative bursts increase peroxynitrite (ONOO⁻) production, resulting in RNA, mRNA, and protein nitration that contributes to programmed cell death and restricts pathogen spread (Izbiańska *et al.*, 2018). The pathogen, however, suppresses host immunity through secreted effectors such as Pi08174, which interfere with defense-related pathways and enhance virulence (Zheng *et al.*, 2025). Infection also induces dynamic changes in host DNA methylation that regulate defense-related gene expression,

with epigenetic reprogramming influencing disease progression (Tian *et al.*, 2025). Resistance is primarily mediated through the hypersensitive response (HR), in which rapid localized cell death limits pathogen growth, while callose deposition and phenolic compound accumulation strengthen cell walls and further restrict pathogen invasion (Vleeshouwers *et al.*, 2000).

Recent advances in genome editing have opened new opportunities for improving late blight resistance. CRISPR/Cas9-mediated disruption of the susceptibility gene *StDND2* significantly reduced disease severity, demonstrating the potential of susceptibility gene editing for developing durable resistance against *P. infestans* (Bibi *et al.*, 2026).

Disease symptoms of late blight

Leaves: Initial symptoms of late blight appear as small (2–10 mm), circular, pale- to dark-green, water-soaked lesions, typically developing at the leaf margins and tips. Under cool and humid conditions, lesions may occur anywhere on the leaf surface, enlarge rapidly, turn dark brown to black, and coalesce, resulting in extensive blighting and rapid leaf death (Lal *et al.*, 2018; Al Harethi *et al.*, 2023; Bagchi *et al.*, 2024). A characteristic diagnostic feature is the presence of white sporulation on the abaxial (lower) surface of infected leaves under humid conditions (Tsedaley, 2014; Al Harethi *et al.*, 2023).

Stems and petioles: Water-soaked lesions on stems and petioles enlarge rapidly into dark brown to black lesions that may develop before or after leaf symptoms. As the disease progresses, these lesions weaken the affected tissues, often causing stem collapse, and serve as important sources of secondary inoculum for further disease spread (Ghorbani *et al.*, 2004; Arora *et al.*, 2014; Kumar *et al.*, 2018).

Tubers: Tuber infection occurs when sporangia are washed from infected foliage into the soil and reach developing tubers. Infected tubers develop irregular, slightly sunken, brown to reddish-brown or purplish lesions on the surface, which extend into the underlying tissues as reddish-brown, granular rot, reducing both tuber quality and storability (Arora *et al.*, 2014; Adolf *et al.*, 2020). Representative symptoms of late blight on leaves, stems, and tubers are shown in Fig. 1.

Epidemiology

The development of potato late blight is strongly influenced by environmental conditions. The disease is favored by cool, humid weather, with temperatures of 10–20°C, prolonged leaf wetness, fog, and heavy dew promoting infection. Sporangial production is greatest at 15–20°C, whereas lower temperatures (10–13°C) stimulate zoospore release, while dry conditions and temperatures above 24°C suppress disease



Fig. 1. Symptoms of potato late blight caused by *Phytophthora infestans*: (A) leaf symptoms, (B) stem symptoms, and (C) tuber symptoms. Images adapted from (A–B) ©Eric Anderson, Crop Science, and (C) ©Anna L. Snowden, CABI.

development (Dey *et al.*, 2014). Leaf wetness duration, soil moisture, and irrigation management further influence sporulation, pathogen dispersal, infection efficiency, disease severity, and epidemic development (Café-Filho *et al.*, 2019).

The dispersal of *P. infestans* occurs primarily through airborne sporangia and water-mediated movement, with seasonal and environmental conditions playing a crucial role in epidemic initiation and spread (Mohaimin *et al.*, 2023; Bregant *et al.*, 2024). Disease gradient studies have shown that infested organic potato fields can act as important mid-season inoculum sources, facilitating pathogen spread to neighboring conventional fields (Zwankhuizen *et al.*, 1998).

Host susceptibility also contributes to epidemic development, with potato plants becoming increasingly susceptible to late blight as they age (Abuley & Hansen, 2021). In addition, climate change is expected to alter the distribution and severity of late blight by modifying temperature, humidity, and rainfall patterns, emphasizing the need for adaptive disease management strategies (Bagchi *et al.*, 2024).

Sustainable management practices

Integrated disease management

Sustainable management of potato late blight relies on an integrated disease management (IDM) approach that combines cultural practices, host resistance, biological control, disease forecasting, and judicious fungicide use to achieve effective and durable disease suppression (Dong & Zhou, 2022; Maurya *et al.*, 2025). The integration of multiple complementary strategies reduces disease pressure, delays fungicide resistance, and promotes environmentally sustainable potato production.

Host resistance forms the foundation of IDM. Advancing this genetic approach, the ICAR-Central Potato Research Institute (ICAR-CPRI) has actively developed next-generation cultivars like *Kufri Ratan*, which incorporates robust resistance to *Phytophthora infestans* with high-yielding traits to anchor sustainable regional IDM frameworks (Singh *et al.*, 2026). The incorporation of resistance genes from wild potato relatives into commercial cultivars has improved durable resistance, although weather conditions and inoculum pressure often exert a greater influence on disease development than cultivar resistance alone, emphasizing the need to combine resistant cultivars with other management practices (Lamichhane *et al.*, 2024; Meno *et al.*, 2025). Disease forecasting models based on weather variables, such as BLITECAST and JHULSACAST, further enhance IDM by optimizing the timing and efficiency of fungicide applications (Lamichhane *et al.*, 2024).

Several studies have demonstrated the benefits of integrating resistant cultivars with fungicides and other cultural practices. Combining resistant cultivars with fungicide applications significantly reduced late blight severity, increased potato yield, and reduced fungicide dependence, whereas the additional benefits of mulching varied with environmental conditions (Demis Gedlu *et al.*, 2022; Kilonzi *et al.*, 2024; Phungula *et al.*, 2025). Similarly, integrating farmyard manure, poultry manure, *Trichoderma harzianum*, and fungicide application reduced late blight severity from 49.05% in the untreated control to 5.35% while increasing tuber yield from 211.68 to 449.40 g plant⁻¹ (Bansal *et al.*, 2022). Strip cropping with grass or maize also reduced disease severity, with grass strips increasing potato yield by 31–33% compared with monoculture (Homulle *et al.*, 2024).

Successful implementation of IDM also depends on farmer knowledge and technological innovation. Farmer training and extension services improve the effective use of fungicides and integrated management practices (Tadiye *et al.*, 2026). In addition, eco-friendly approaches, including plant extracts, essential oils, biological control agents, RNA interference, and nanoencapsulation, represent promising alternatives for sustainable late blight management (Hari *et al.*, 2025). Decision-support tools such as the Taguchi optimization approach further facilitate IDM by identifying cultivar selection as a key factor influencing disease management and optimizing integrated control strategies (Ritchie *et al.*, 2025).

Host plant resistance

Host plant resistance is one of the most sustainable strategies for managing potato late blight because it reduces reliance on fungicides while providing long-term disease suppression (Paluchowska *et al.*, 2022; Dechen Angmo *et al.*, 2023). Integrating conventional and molecular breeding approaches has accelerated the development of durable resistant cultivars. Advanced technologies, including marker-assisted selection, somatic hybridization, gene pyramiding, and CRISPR-based genome editing, have facilitated the incorporation of multiple late blight resistance (*Rpi*) genes, resulting in broader and more durable resistance against *Phytophthora infestans* (Berindean *et al.*, 2024; Sahito *et al.*, 2026). The successful development of potato populations carrying stacked *Rpi* genes further demonstrates the potential of gene pyramiding to enhance resistance durability (Keijzer *et al.*, 2021).

Field evaluations have confirmed the effectiveness of resistant cultivars in suppressing late blight while maintaining high productivity. A resistant potato clone (C2-5)

carrying multiple resistance genes sustained only 0.4–0.5% foliage damage and produced 59.5 t ha⁻¹ without fungicide application (Islam *et al.*, 2022). Similarly, resistant cultivars maintained less than 1% disease severity compared with 60–78% in susceptible cultivars grown without fungicide treatment (Kilonzi *et al.*, 2024). Maincrop cultivars combining moderate-to-high late blight resistance with yields of up to 49 t ha⁻¹ and starch contents exceeding 19% demonstrate that disease resistance can be successfully integrated with desirable agronomic traits (Asakaviciute *et al.*, 2025). In addition, the climate-resilient cultivar INIA 333-CHUGAYNA exhibited frost tolerance, field resistance to late blight, high yield, and reduced fungicide requirements, highlighting the importance of resistant cultivars for climate-resilient potato production (Cabrera *et al.*, 2025). Examples of potato cultivars and genotypes exhibiting resistance to late blight across different countries are summarized in Table 1.

Cultural management

Cultural practices play a fundamental role in integrated late blight management by reducing the survival, reproduction, dispersal, and infection of *Phytophthora infestans*, thereby lowering primary inoculum and disease pressure (Tsedaley, 2014; Lal *et al.*, 2018; Rhouma *et al.*, 2024; Maurya *et al.*, 2025). Effective sanitation measures include crop rotation, destruction of cull piles and volunteer potato plants, removal of infected plants and crop debris, and vine desiccation before harvest to minimize pathogen survival between growing seasons (Demissie, 2019; Lal *et al.*, 2018).

Agronomic practices such as proper irrigation management to reduce leaf wetness, adequate plant spacing to improve air circulation, and the use of certified disease-free seed tubers further limit disease

Table 1. Comparative Performance of Potato Cultivars and Genotypes Resistant to Late Blight (*Phytophthora infestans*) in Different Countries

Cultivars/Genotypes	Country/Region	Peak Foliar Disease Severity (%)	Average Potato Yield (t/ha)	Research Source
'Goda', 'Rasa'	Lithuania	3.0%-35.0%	38.5-45.2 t/ha	Asakaviciute <i>et al.</i> , 2025
'CIP-Matilde'	Peru	<5.0%	32.0-37.5 t/ha	Gastelo <i>et al.</i> , 2024
'Unica'	Kenya	12.5%	28.4 t/ha	Kilonzi <i>et al.</i> , 2024
BARI Alu 77 BARI Alu 53	Bangladesh	8.0%-14.5%	30.0-34.8 t/ha	Islam <i>et al.</i> , 2022
Regional Genotypes (High Altitude)	Ethiopia	18.0%-62.0%	12.1-24.5 t/ha	Biri <i>et al.</i> , 2026
'Bioimpuls' Selections	Netherlands	<2.0%	35.0-41.0 t/ha	Keijzer <i>et al.</i> , 2022
'Bionica' / 'Toluca'	Denmark	0.0%-10.0%	38.0-44.0 t/ha	Abuley & Hansen, 2022
Selected Phenotypes	Estonia	15.0%-40.0%	26.0-33.0 t/ha	Agho <i>et al.</i> , 2023
'Cooperation-88' (C88)	China	<8.0%	30.0-45.0 t/ha	YAAS, 2024
'Khumal Ujjwal'	Nepal	11.0%-15.0%	13.9-18.5 t/ha	NARC, 2023
'Kufri Himalini'	India	16.21 %	45 t/ha	Chakraborty <i>et al.</i> , 2022
'Atlantic' (with RB gene)	United States	4.0%-8.5%	42.0-48.0 t/ha	USDA-ARS, 2024

development (Sahu, 2012; Demissie, 2019). Adjusting planting dates can also reduce disease pressure; Chulda *et al.* (2021) reported that late planting enabled potato crops to escape periods of peak late blight infection where climatic conditions were suitable. Nitrogen management is equally important, as excessive nitrogen application (320 kg ha⁻¹) increased late blight severity and reduced yield compared with a moderate application rate of 160 kg ha⁻¹ under intermediate disease pressure (Juárez *et al.*, 1999). In addition, mulching reduces late blight by minimizing rain splash, thereby limiting the dispersal of *P. infestans* sporangia and reducing primary inoculum (Waheed *et al.*, 2023). Proper postharvest storage of healthy tubers further minimizes the carryover of inoculum to subsequent cropping seasons (Sahu, 2012).

Biological management

Biological control is a promising and environmentally sustainable approach for managing potato late blight because beneficial microorganisms suppress *Phytophthora infestans* through antagonism, competition, mycoparasitism, antimicrobial metabolite

production, and induction of plant defense responses (Goutam *et al.*, 2018; Wang & Long, 2023). The effectiveness of biological control can be further enhanced by combining agents with different modes of action and integrating them with other disease management practices within an integrated pest management (IPM) framework (Wang & Long, 2023).

Numerous microbial biocontrol agents have demonstrated efficacy against late blight. Species of *Trichoderma*, *Bacillus*, *Pseudomonas*, *Streptomyces*, *Pythium oligandrum*, *Glomus*, *Xenorhabdus*, and *Chaetomium*, as well as chitosan hydrochloride, significantly reduced disease severity and, in many cases, promoted potato growth and yield (Wharton *et al.*, 2012; Yao *et al.*, 2015; Slininger *et al.*, 2007; Daaboub *et al.*, 2022; Jin *et al.*, 2023; Soyong & Ratanacherdchai, 2023; Pöldmets *et al.*, 2025). For example, *Trichoderma harzianum* and *Bacillus subtilis* effectively reduced seed-piece decay (Wharton *et al.*, 2012), *Trichoderma* isolate HNA14 significantly suppressed late blight while enhancing plant growth (Yao *et al.*, 2015), and combining *Streptomyces* with

biochar provided greater disease suppression than either treatment alone (Jin *et al.*, 2023). Likewise, mixtures of *Pseudomonas fluorescens* strains were more effective than individual strains in controlling late blight (Slininger *et al.*, 2007).

Despite their considerable potential, most biological control agents provide lower and more variable disease control than synthetic fungicides when used alone (Daaboub *et al.*, 2022; Pöldmets *et al.*, 2025). However, integrating biological control agents with fungicides or other sustainable management practices can substantially improve disease suppression. For instance, the combined use of *Glomus* spp. and *Pythium oligandrum* with fungicides significantly reduced late blight severity, while a *Chaetomium*-based mycofungicide integrated with biological fertilizers achieved disease control comparable to that of chemical fungicides (Cwalina-Ambroziak *et al.*, 2015; Soyong & Ratanacherdchai, 2023).

Botanical extracts

The widespread and repeated use of synthetic fungicides has accelerated the development of fungicide resistance in *Phytophthora infestans*, increasing interest in botanical extracts as environmentally friendly alternatives for late blight management (Mehmood *et al.*, 2022; Hari *et al.*, 2025). Plant extracts and essential oils possess strong antifungal activity due to their high concentrations of bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids, and other secondary metabolites that inhibit pathogen growth and development (Hari *et al.*, 2025).

Numerous plant-derived products have demonstrated significant efficacy against potato late blight. Garlic and neem extracts effectively suppressed disease development, with garlic reducing disease incidence to

5.81% compared with 61.18% in the untreated control (Mehmood *et al.*, 2022). Ethanolic extracts of clove and black pepper completely inhibited *P. infestans* mycelial growth in vitro, while thyme also exhibited strong antifungal activity (Shebannavar *et al.*, 2022). Similarly, extracts of *Aloe vera*, ginger (*Zingiber officinale*), African basil (*Ocimum gratissimum*), and *Frangula alnus* bark significantly reduced late blight severity and improved potato yield, highlighting their potential as eco-friendly components of integrated disease management programs (Manju *et al.*, 2024; Musa *et al.*, 2025; Saxena *et al.*, 2025).

Chemical control

Chemical control remains the primary strategy for managing potato late blight because fungicides provide rapid and reliable disease suppression when applied preventively and integrated with other management practices (Babarinde *et al.*, 2025; Dey *et al.*, 2024). Preventive spray programs consisting of contact fungicides followed by systemic or translaminar fungicides effectively reduce disease incidence and severity while significantly increasing potato yield and profitability (Dey *et al.*, 2024).

Several fungicides have demonstrated excellent efficacy against *Phytophthora infestans*. Recently approved products such as Ninja 56 SC, Zam Gold 50 WP, and Oracol 70 WP achieved more than 95% disease suppression under field conditions (Rahman *et al.*, 2026). Similarly, cymoxanil + mancozeb provided nearly complete control of late blight and produced the highest tuber yields when used as a preventive fungicide, while its combination with hexaconazole also showed strong curative activity (Siddique & Aktar, 2016). Ridomil Gold and Ridomil MZ (metalaxyl + mancozeb) consistently outperformed mancozeb and chlorothalonil, significantly reducing disease severity

and increasing tuber yield (Inam-ul-Haq *et al.*, 2008; Kefelegn *et al.*, 2012). Field studies in Nepal further demonstrated that dimethomorph, fenamidone + mancozeb, and mancozeb effectively suppressed late blight, with dimethomorph providing the greatest disease control and economic return (Khadka *et al.*, 2020). In addition, cyazofamid, mandipropamid, and oxathiapiprolin + benthiavalicarb have emerged as effective alternatives to mancozeb for late blight management (Naim & Cohen, 2023).

Despite their effectiveness, the extensive use of fungicides has increased the risk of fungicide resistance in *P. infestans*. Reversible resistance to mancozeb and shifts in fungicide sensitivity associated with the increasing genetic diversity of pathogen populations highlight the importance of fungicide rotation, resistance monitoring, and integration of chemical control with cultural, biological, and host resistance strategies to ensure sustainable disease management (Fan *et al.*, 2025; Babarinde *et al.*, 2025). Compared with alternative chemical treatments such as ozone (O₃) and hydrogen peroxide (H₂O₂), conventional fungicides remain the most effective option for suppressing late blight and maximizing potato yield (Skrobacz *et al.*, 2026).

Late blight and climate change

Climate change is reshaping plant-pathogen interactions by altering the survival, distribution, virulence, and epidemiology of plant pathogens, thereby increasing disease pressure and crop losses worldwide (Ali *et al.*, 2024; Kumar & Mukhopadhyay, 2024). It is also projected to shift the geographical distribution of potato pests, creating new areas of infestation and emphasizing the need for early monitoring and adaptive pest management strategies (Xian *et al.*, 2023).

Potato late blight is highly sensitive to changes in temperature, humidity, and rainfall. In Finland, warmer and wetter conditions resulted in late blight outbreaks occurring 2–4 weeks earlier during the late 1990s and increased the likelihood of epidemics by 17-fold, leading to greater fungicide use and illustrating the impact of climate change on disease management (Hannukkala *et al.*, 2006). However, simulation studies suggest that the effects of climate change on late blight are region-specific. Although early disease onset causes the greatest yield losses, increasing temperatures may suppress *Phytophthora infestans* more than potato growth in some environments, resulting in variable disease responses under future climates (González-Jiménez *et al.*, 2023).

Projected climate scenarios (RCP 4.5 and RCP 8.5) indicate temperature increases of up to 3.8°C and highly variable rainfall (–721 to +448 mm), with potato yields expected to decline by 37–59%, highlighting the crop's vulnerability to climate change (Pushpalatha *et al.*, 2021). Strengthening adaptation capacity through farmer education, participation in farmer groups, improved agricultural infrastructure, and supportive institutional and economic policies will be essential for enhancing the resilience of potato production under changing climatic conditions (Purwanti *et al.*, 2022).

CONCLUSION

Potato late blight, caused by *Phytophthora infestans*, remains one of the most destructive diseases affecting potato production worldwide, resulting in substantial yield losses and economic damage. The pathogen's rapid evolution, genetic diversity, and ability to develop fungicide resistance, together with the increasing influence of climate change, continue to challenge

effective disease management. Advances in understanding the biology, epidemiology, host-pathogen interactions, and disease cycle of *P. infestans* have significantly improved the development of integrated management strategies. Sustainable control of late blight cannot rely on a single approach but instead requires the integration of host plant resistance, cultural practices, biological control agents, botanical products, disease forecasting systems, and judicious fungicide application. The adoption of integrated disease management (IDM) strategies offers the most effective and environmentally sustainable approach to minimizing disease losses while reducing dependence on synthetic fungicides and improving potato productivity.

FUTURE PROSPECTS

Future research should prioritize the development of durable late blight-resistant cultivars through conventional breeding, gene pyramiding, marker-assisted selection, and genomic selection, utilizing the diverse resistance available within the cultivated potato gene pool. Where existing resistance sources are insufficient, novel resistance genes from wild *Solanum* species should be introgressed into cultivated germplasm through hybridization and modern breeding approaches. CRISPR-based genome editing can subsequently be explored to complement conventional breeding and accelerate the development of improved resistance. Greater attention should also be given to biological control agents, botanical fungicides, RNA interference technologies, and nano-based formulations as sustainable alternatives to conventional fungicides. The integration of artificial intelligence, remote sensing, unmanned aerial vehicles, precision agriculture, and weather-based disease forecasting models will enhance early disease detection and optimize management

decisions. Continuous monitoring of *P. infestans* population dynamics, virulence, and fungicide sensitivity is essential for detecting emerging pathogen genotypes and fungicide resistance. Climate change adaptation should also be incorporated through climate-resilient cultivars, location-specific integrated disease management programs, and strengthened farmer education and extension services. Collaborative efforts among researchers, breeders, policymakers, and farmers will be critical for translating scientific advances into practical and sustainable solutions for the long-term management of potato late blight and global food security.

ETHICAL STANDARDS

This review article does not involve experiments on humans, animals, or living subjects. The authors declare that the work complies with the current laws and regulations of the country in which it was performed.

LEGAL REQUIREMENTS

The author declares that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. The author has read and approved the manuscript and agrees to its submission.

PERMISSIONS

The author confirms that all figures and tables included in this manuscript are original and that all sources of information have been appropriately cited. No copyrighted material requiring permission has been reproduced in this manuscript.

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