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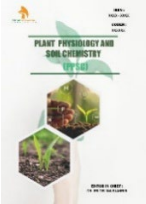

RESEARCH ARTICLE

POTATO LATE BLIGHT CAUSED BY *Phytophthora infestans*; AN OVERVIEW ON PATHOLOGY, INTEGRATED DISEASE MANAGEMENT APPROACHES, AND FORECASTING MODELS

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ABSTRACT

Late Blight of potato, caused by fungal pathogen *Phytophthora infestans*, is a highly destructive disease that affects potato crops on a global scale. The pathogen, *P. infestans*, shows a complex biology, with both sexual and asexual life cycles that involve the production of hardy oospores. The symptoms of late blight are severe, leading to the destruction of foliage and the rotting of tubers during storage. The interaction between *Phytophthora infestans* and its host plants is a complex interplay of molecular and physiological mechanisms. Understanding these intricate processes is crucial for developing effective strategies to combat this devastating pathogen, as it continuously evolves to overcome plant defenses, posing ongoing challenges to agriculture. To effectively manage this disease, an integrated disease management (IDM) approach is necessary, which combines cultural practices, host resistance, biological control agents, and judicious chemical control measures. Eliminating sources of inoculum through strict sanitation, utilizing resistant cultivars, employing biocontrol agents such as *Trichoderma spp.*, and implementing fungicide schedules are essential components of this approach. Furthermore, incorporating genes that confer resistance from wild relatives into commercial cultivars also facilitates efficient disease management. Accurate disease forecasting models incorporate weather data and serve as invaluable tools for decision support, optimizing the timing and economics of fungicide applications. Models like BLITECAST, JHULSACAST, and advanced process-based systems are continuously being improved. This comprehensive review explores the latest research on this devastating oomycete pathogen, providing valuable perspectives for scientists, breeders, growers, and forecasting models involved in sustainable late blight management.

KEYWORDS

Disease, Fungicides, Late blight, Management, *Phytophthora infestans*, Potato

1. INTRODUCTION

Potato (*Solanum tuberosum* L.), a member of Solanaceae family, is an agricultural crop cultivated as a staple food in over 150 nations, including Nepal which accounts for 2.17 percent of the GDP and 6.57 percent of the agriculture GDP of Nepal (Shrestha et al., 2018). Potatoes are prone to various major diseases like late blight, early blight, powdery scab, wart, etc. Among these diseases in potatoes, late blight is a devastating global problem that affects all areas where potatoes, tomatoes, peppers, and eggplants are grown. Late blight can cause substantial production losses and has had historic significance such as the Irish Famine in the 19th century. The disease affects all stages of plant growth, including tubers and stems, and can result in 100% yield loss (Singh, 2023). Late blight of potato results in significant economic losses worldwide. Estimated global economic losses due to late blight range from 3 to 5 billion dollars annually (Islam et al., 2021). In developing countries, where effective chemical control is often too expensive, potato late blight frequently causes over 60% yield loss (Copeland et al., 1993). As potato is a very significant crop and late blight caused by *Phytophthora* causes heavy damage to the yield of potato every year, it is a must to know about the disease-causing agent, its proper management practices, and proper forecasting models to predict and prevent the disease before causing any harm.

The pathogen causing late blight can infect roots, tubers, and shoots, potentially resulting in complete crop loss under ideal conditions (Dey et al., 2022). *Phytophthora infestans* release various proteins during infection, including cell wall-degrading enzymes, proteins similar to microbe-associated molecular patterns, and effectors that target the apoplast (Lacaze et al., 2023). The haustorium, a pathogen structure, penetrates the host cell wall and absorbs nutrients and water. The host cell wall is a major site of protein secretion during infection. The crucial measures include cultural control, the utilization of resistant varieties, and chemical control (Tsedaley, 2014). However, prevention of disease is more important than its control after already causing significant crop destruction. Disease forecasting models help us predict and prevent the outbreak of destructive diseases by analyzing the atmospheric and environmental parameters.

Disease prediction models have been created to assist farmers in efficiently controlling the spread of diseases. These models utilize various factors, including weather data to predict the likelihood of late blight outbreaks. One of the simulation models that can be discussed is BLIGHTSIM. BLIGHTSIM is designed to simulate the response of *Phytophthora infestans* to the changes in daily temperature and humidity caused by climate change (Khandan et al., 2020). A model that is process-

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based and dynamic has also been created to forecast the likelihood of late blight occurrence in Norway (Hjelkrem et al., 2021).

2. BRIEF HISTORY OF LATE BLIGHT OF POTATO

Late blight disease, caused by *Phytophthora infestans*, has its origin in South America, specifically in the Andean region. The disease was first reported during the 1840s in the United States and Europe, leading to the Irish potato famine (1845-1852). Reverend Berkeley and Anton De Bary were pioneers in identifying the fungus as the causal agent of late blight and believed it was imported from the Andes of South America (Saville et al., 2016). However, recent studies suggest that central Mexico is the center of origin for *P. infestans*, with the pathogen being introduced to the United States in 1842 and then to Europe in 1845 (Duan et al., 2021). The Irish Potato Famine, which occurred between 1845 and 1852, had devastating effects on the population of Ireland. The famine resulted in significant potato losses and subsequent human losses through death and migration (Powderly, 2019). The impact of the famine was profound, leading to a decline in Ireland's population by over one-third and a subsequent diaspora of almost 80 million people, many of whom settled in America (Saville et al., 2016). Control of *Phytophthora infestans* during the Irish famine involved various management strategies, including cultural, varietal, and chemical control (Hwang et al., 2014). Cultural practices such as reducing inoculum load and implementing integrated disease management were found to be effective in managing the disease. The use of resistant potato varieties was also considered an important strategy for controlling late blight. However, the diversification of *P. infestans* and its ability to overcome host resistance posed challenges to long-term management (Tsedaley, 2014). Chemical control, through the use of fungicides, was evaluated but the pathogen showed a remarkable capacity for change in response to fungicides (Lal et al., 2018). Additionally, forecasting was identified as a valuable tool for managing late blight, as it allowed for timely information dissemination to end users and helped reduce primary sources of infection. Overall, a combination of these strategies led to effective control of *P. infestans* during the Irish famine. Late blight disease in potato, still today, continues to be a major concern for potato breeders and has significant economic consequences worldwide. It still poses a serious threat to potato production more than 160 years later, especially in the colder and wetter regions (Cooke et al., 2011). It's been estimated that *P. infestans* has caused a loss of about 12 billion dollars per annum, out of which about 10-billion-dollar losses occurred in developing countries. The amount of loss it has caused is proof of how severe the disease is (Haverkort et al., 2009). Efforts have been made to develop resistant potato cultivars using conventional and molecular techniques. Biological control methods, such as the use of antagonistic microorganisms and induced resistance have shown potential in controlling late blight.

3. PATHOLOGY OF *Phytophthora infestans*

3.1 Causal pathogen of Late Blight

The late blight of potato is caused by *Phytophthora infestans* (Mont.) de Bary. The pathogen was initially identified by Montagne as *Botrytis infestans* (Mont.) in 1845. However, in 1846, De Bary renamed it *Phytophthora infestans* which is why it is currently known as *Phytophthora infestans* (Mont.) De Bary (Ifeduba, 2021). The genus *Phytophthora* has more than 120 recognized species (Martin et al., 2014) all of which are harmful to plants. In terms of morphology, they look like a coenocytic, hyaline, freely branching mycelium. The hyphae of *Phytophthora* species are typically wider in diameter (5-7 µm) and slow growing with branching at an approximate right angle. However, the definitive differentiation between them lies in the mode of zoospore differentiation and discharge. It is a hemibiotroph; the primary biotroph stage is followed by the formation of secondary necrotrophic hyphae that multiply by killing host tissues before they spread (Perfect & Green, 2001). They colonize a variety of host tissues, including fruit, roots, tubers, herbaceous stems, woody trunks, and foliage. *P. infestans* is an oomycete pathogen that is more closely linked to brown algae than to actual fungi (Gunderson et al., 1987). The life cycle of *P. infestans* consists of both sexual and asexual phases, but the majority of reproduction is asexual. On infected host tissue, the bacteria develop sporangia, which can either germinate directly to form infection hyphae or release zoospores which can cause secondary infections. *P. infestans* has both homothallic and heterothallic strains. Homothallic strains are capable of producing oospores on their own, while heterothallic strains require both A1 and A2 mating types to produce oospores (Retes-Manjarrez et al., 2022). The production of oospores is important for disease epidemiology as they serve as primary inoculum in subsequent growing seasons (Ariyoshi et al., 2021).

3.2 Taxonomy of Pathogen

The genus *Phytophthora* is a not true type fungus and it is categorized as an oomycete in the phylum Oomycota, order Peronsporales, and kingdom Chromista (Birch and Whisson, 2001). Phytophthora belongs to the kingdom Stramenopila, phylum Oomycota, order Peronosporales and family Pythiaceae (Lamour et al., 2007). *Phytophthora* comprises 60 identified species, such as *P. cactorum*; a significant apple pathogen, *P. capsicum*; a pepper-affecting plant, *P. citrophthora*; a citrus pathogen, and *P. cinnamomi*; a woody plant that affects numerous woody plants, including conifers (Erwin and Ribeiro, 1996). Therefore, it is possible to differentiate members of Phytophthora from other fungal species due to the presence of characteristics such as motile zoospores with whiplash and tinsel flagella, cell walls made of cellulose and glucans rather than chitin, multiple sporangia produced on each sporangiophore and diploid vegetative cells (Zentmyer 1983, Arora et al., 2014).

3.3 Morphology of the Pathogen

Morphological features of *Phytophthora infestans* revealed terminal sporangia with a significant limoniform papillate shape (Adhaileh et al., 2023). There are eight different forms of sporangia in Cameroon that suggested variability among them; they were oval to ellipsoid, pip form, elliptic, sub globose, globose, ovoid, and lemoniform. The white, fluffy mycelia of *P. infestans* have beige tones due to the presence of sporangia with hyphae that are ramified, and hyaline, and measure 5 to 8 µm in diameter (Mugao, 2023). The average sizes of the sporangia were 60.5 µm in length and 31.7 µm in width (Shimelash and Dessie, 2020). The released zoospore has an uninucleate and biflagellate structure. Furthermore, chlamydospores, also known as "asexual thick-walled spores," are intercalary and terminal, and their thick walls differentiate them from hyphal swelling (Adhaileh et al., 2023).

3.4 Development and Epidemiology

Late blight progresses more rapidly under cool, moist conditions than in hot, dry weather. The development of diseases is influenced by several factors including temperature, relative humidity, light intensity and quality, photoperiod, fogginess, leaf wetness, rainfall, dew, wind speed, and others. The main variables that control the rates of epidemic development are variability, infectivity, and rates of production and dispersal of inoculum (Bashi et al., 1982). The ideal temperature range for the growth of fungi is 16–24 °C. The 16–20°C and 1-6°C ranges of maximum and minimum temperatures were found to be conducive for the potato blight disease. Also, similar conditions that aid in the development of the disease include relative humidity, rainfall, and wind speed in the range of 63–71%, 1.5–3.75 mm, and 1–5.5 km/h, respectively (Ahmed et al., 2015). The growth and susceptibility of host plants also affect the development of late blight disease. Moreover, the existence of moisture without charge on the surface of the plant is a critical element for the initiation of sporangia and the subsequent invasion of host tissues (Fry et al., 1993).

3.5 Late Blight Development Cycle

The late blight Development Cycle is shown in figure 1.

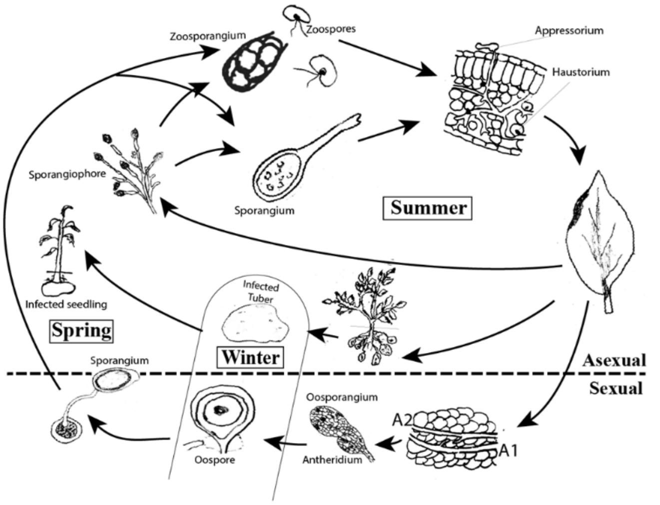

Figure 1: The life cycle of the late blight pathogen *Phythophtora infestans*

3.5.1 Overwintering and Survival

Overwintering inoculum is the source of primary infections in newly planted potatoes (Pscheidt, 1985). In plant detritus, soil, infected tubers, or other host plants of the same family, the pathogen overwinters as mycelium or conidia. For five to eight months, the inoculum in detritus in uncultivated soil is still contagious. Most often, spores persist in diseased seeds and debris. The primary determinants of the survival of spores in trash and seed are meteorological, edaphic, and biotic conditions. Fallow, arid fields are ideal for the fungus' survival (Rotem, 1994).

3.5.2 Dispersal

Multinucleate sporangia and uninucleate motile zoospores represent the primary dispersal stages (Whisson et al., 2016). Dispersal of sporangia takes place in the morning when there is a rise in temperature and a fall in relative humidity (Arora, 2014). Wind, rain, mechanical transport, animals, and insects are the principal methods of dissemination of potato blight. For example, the Colorado potato beetle (*Leptinotarsa decemlineata*) spreads the fungus when it feeds on the leaves of infected plants (Rands, 1917). However, spore dispersal and other climatological parameters don't seem to be significantly correlated. The concentration of spores rises in direct proportion to the occurrence of the disease because there is a reservoir of spores that must be distributed during the day. Using spore traps, peak spore dispersal occurred two hours before the hottest and driest part of the day (Rotem, 1964).

3.5.3 Inoculation

The duration of leaf wetness, inoculum density, temperature, and their interactions determine spore germination and infection in potato plants (Arora et al., 2014). *P. infestans* sporangia may germinate directly, or release zoospores to initiate infection. Germination takes place within hours and may enter host tissue through natural openings (stomata) or form an appressorium-like swollen germ tube, beneath which penetration of host epidermal cells occurs that leads to spherical primary infection vesicles (Whission et al., 2016).

3.5.4 Penetration

The zoospores home at the root zone, encysts, and secrete adhesive that glues them to the root surface. The germ tube that emerges from the cyst penetrates the root epidermis, usually expanding intracellularly along the anticlinal cell wall, and the haustoria can develop in cortical cells (Hardham, 2001). A penetration peg is formed under favorable conditions that pierce the cuticle and penetrates the underlying plant cell, forming an infection vesicle subsequently in the epidermal cell and hyphae grow into the mesophyll cell layers (Van West and Vleeshouwers, 2004).

3.5.5 Infection

Motile, biflagellate zoospores that are chemotactically attracted to nearby roots are typically the first to commence a successful infection (Hardham, 2001). *P. infestans* initiates most of the infection through asexual sporangia, which only infects living tissue, extracting nutrients from the apoplast or extra haustorial space, and terminating the infection with sporulation and host necrosis (Leesutthiphonchai et al., 2018). Infection is promoted by effector proteins, which manipulate and alter the host's immune response.

3.6 Symptoms

Late blight of potato, caused by *Phytophthora infestans*, includes major symptoms such as water-soaked light to dark brown spots on leaves and stems (as shown in Figure 2), and slightly depressed areas with a reddish-brown color on white tubers (Adolf et al., 2020).

Figure 2: Late blight potato symptoms on leaves and stem seen at AFU Rampur, Chitwan, Nepal

Irregularly shaped, water-soaked lesions are observed on leaves, which progress to brown, shriveled leaves during humid conditions (Arakeri et al., 2015). Normally hard, dry, and firm, the diseased tubers can become attacked by soft rot-causing bacteria and rot in fields and stores (Arora et al., 2014). Late blight development is influenced by the age of the plant as well as environmental factors including increased humidity, temperature, and abiotic stress (Holley et al., 1985). It begins as irregular, light green lesions around the tips and margins of the leaves and progresses to big, brown to purplish-black necrotic patches. Although it affects all foliar parts, it is more common in the leaves, stems, and tubers (Lal et al., 2018). The disease rapidly enlarges the water-soaked lesions on the leaves, resulting in dark, blighted areas and eventually the destruction of the plant (Govers, 2005). Some of the common symptoms seen in late blight-infected plants that might be similar in other diseases include stunted plant growth, necrotic lesions on leaves, rotting of tubers, etc.

3.7 Interaction between *Phytophthora infestans* and its Host Plants

The interaction between *Phytophthora infestans* and its host plants is complex, involving numerous molecular strategies that enable the pathogen to infect and suppress the plant's defenses. *Phytophthora infestans* exhibits a hemi-biotrophic lifestyle, shifting from a biotrophic to a necrotrophic phase during its infection cycle. This process includes chemotactic movement towards the host and the subsequent invasion of host tissues (Aswathi et al., 2024). The pathogen employs specialized structures for invasion, known as "naifu" invasion, which allow it to breach the plant cell walls efficiently. *P. infestans* secretes various effectors, such as RXLR effectors, to manipulate host cellular processes. For example, the effector Pi23014 targets the host RNA-binding protein NbRBP3a, weakening plant immunity and increasing susceptibility (Li et al., 2024). Another effector, Pi07586, functions within the host nucleus to downregulate genes related to defense, further aiding the infection by modulating the host's immune response (Xiong et al., 2023). Below is an explanation of the physiological, molecular and cellular aspects of the interaction between *Phytophthora infestans* and host plants:

3.7.1 Physiological Aspects

The physiological aspects of interaction between *Phytophthora infestans* and the host plants are given in Table 1.

Table 1: Physiological aspects of interaction between *Phytophthora infestans* and the host plants

S.N.	Description	References
1.	The physiological interaction between *Phytophthora infestans* and its host plants is marked by a complex mechanism centered on its hemi-biotrophic lifestyle. In the early stages, *P. infestans* use effector proteins like the RXLR effector Pi23014 to manipulate the host's cellular processes and suppress immunity. This involves targeting proteins such as NbRBP3a to downregulate defense pathways, making the host more susceptible to infection.	(Li et al., 2024)
2.	The infection process is characterized by chemotactic attraction, penetration, and nutrient scavenging from living host cells, essential for the pathogen's growth and proliferation.	(Aswathi et al., 2024; Rodenburg et al., 2019)
3.	Additionally, the pathogen's transition from the biotrophic to the necrotrophic phase triggers host defense responses, including PAMP Triggered Immunity (PTI) and Effector Triggered Immunity (ETI), which are part of a continuum of defense mechanisms.	(Naveed et al., 2020)
4.	The mechanical aspect of the infection is enhanced by an actin-based mechanostat that sharpens the hyphal tip for effective penetration. Gaining a deeper understanding of these interactions is crucial for developing strategies to control *P. infestans*.	(Bronkhorst et al., 2022)

3.7.2 Cellular and Molecular Aspects

The cellular and molecular interactions between *Phytophthora infestans* and host plants involve a series of mechanisms that enable infection and trigger host defense responses. These interactions are pivotal in devising effective strategies to combat this destructive pathogen. The detailed discussion is done in Table 2.

Table 2: Cellular and molecular interactions between *Phytophthora infestans* and host plants

S.N.	Steps	Description	References
1.	Mechanisms of Infection	1. *Phytophthora infestans* follow a hemibiotrophic lifestyle, transitioning from a biotrophic to a necrotrophic phase during infection, which includes chemotactic attraction and penetration of host tissues.	(Aswathi et al., 2024).
		2. The pathogen uses specialized hyphal tips, supported by an actin-based mechanostat, to effectively penetrate plant surfaces by converting turgor pressure into localized invasive forces.	(Bronkhorst et al., 2022)
2.	Host Defense Responses	1. Upon infection, *P. infestans* secretes RXLR effectors, such as Pi23014, which target host proteins like NbRBP3a to suppress plant immunity, leading to the downregulation of defense pathways.	(Li et al., 2024)
		2. Host plants counteract through PAMP Triggered Immunity (PTI) and Effector Triggered Immunity (ETI), involving the production of antimicrobial compounds and fortification of cell walls.	(Aswathi et al., 2024)
3.	Coevolution and Adaptation	1. The ongoing molecular coevolution between *P. infestans* and its host plants is evident as the pathogen evolves virulent strains that alter effector proteins to evade detection, highlighting the dynamic nature of these interactions.	(Aswathi et al., 2024)
		2. While there has been significant progress in understanding these interactions, many fundamental questions remain unanswered, especially concerning spore biology and haustorium function, which are essential to fully comprehend the pathogenicity of *Phytophthora infestans.*	(Boevink et al., 2020)

4. INTEGRATED DISEASE MANAGEMENT (IDM) APPROACHES

As *Phytophthora infestans* is evolving at a faster rate with wider adaptability, ecofriendly management practices should be preferred. Effective management practices are crucial in preventing and controlling the spread of disease. Due to sexual reproduction and several migrations of *P. infestans*, new genotypes of the pathogen with increased aggressiveness and the ability to overcome the effectiveness of fungicides have been constantly emerging which has further complicated the management of late blight (Majeed et al., 2014). In order to manage late blight effectively, a multimodal strategy called integrated disease management (IDM) is required (Rohuma et al., 2024). An integrated disease management approach makes use of every technique that is available to maximize disease control. This strategy includes several considerations like the influence of prevailing weather on the pathogen life cycle, fungicide residue on crop, physical method, chemical method, biological method, late blight resistance of the cultivar being grown, pathogen characteristics, host-pathogen interaction, mechanism of disease development etc. (Small et al., 2015, Islam et al., 2016). IDM offers a complete and sustainable method for controlling late blight, protecting potato crops, and enhancing food security by strategically integrating these components (Rohuma et al., 2024). Each element is essential to lowering the impact of disease, minimizing yield losses, and maintaining the resilience and long-term health of agricultural ecosystems (Ivanov et al., 2021). Host plant resistance is the most practically applied, economically practicable, ecologically beneficial, and socially acceptable disease management approach for potato late blight in an integrated disease management system (Ojiewo et al., 2010). Fungicides could be used as the active element of integrated disease management if consideration was given to their nature, modes of action, and relative influence on leaf, stem, and tuber infection caused by *P. infestans* (Cooke et al., 2011). When dealing with newly emerging pathogen strains or in situations where disease pressure is severe, the strategic application of target fungicides can be quite beneficial in the sustainable management of late blight (Ivanov et al., 2021). Studies have indicated that utilizing chemical fungicides such as Krilaxyl Gold, along with botanical extracts of garlic, neem, bakaino, and biocontrol agents like Phytoderma, can greatly reduce late blight severity and enhance tuber yield (Adhikari et al., 2023). Moreover, combining synthetic fungicides like Ridomil with specific potato varieties like Belete has proven to be successful in decreasing late blight severity and increasing tuber yield, highlighting a cost-effective advantage (Singh, 2023). Additionally, integrating tuber dressing with Dimethomorph, soil amendment with *Trichoderma viride* and FYM, and foliar application of SAR chemicals and fungicides have shown efficacy in decreasing late blight incidence and intensity, resulting in higher yield gains and improved tuber grades (Teshome et al., 2022). Crop rotation, intercropping, proper spacing, field sanitation, and timely plantings are examples of cultural practices that focus on providing favorable conditions that can reduce the impact of disease (Schiffer-Forsyth et al., 2023). These integrated approaches present promising solutions for efficiently managing late blight diseases in potato crops.

4.1 Resistance

Resistance is defined as the ability of a plant variety to restrict the growth or development of a specified pest and disease causing pathogen and minimization of the damage when compared to susceptible plant varieties under similar environmental conditions. Resistance to control pathogenesis is mainly due to the molecular interaction between the cell surface of the host plant and the pathogen. The presence of a resistance gene/allele enables plants to identify pathogens and trigger inducible defenses, determining many plant-pathogen interactions (Grant et al., 1998). Plants employ different types of resistance mechanisms to protect against pathogens. One type is based on the recognition of pathogen avirulence (Avr) genes by resistance (R) genes, leading to hypersensitivity reactions and cell death, which restrict pathogen development (Majumdar et al., 2023). Another type of resistance is based on the defense response generated by recognition events, involving resistant gene analogs (RGAs) (Kaur et al., 2022). Understanding these different types of resistance mechanisms is crucial for developing strategies to enhance disease resistance in plants.

4.1.1 Host Plant Resistance

When a potato plant comes into contact with *P. infestans* for the first time, its defenses are triggered. Plant activators activate the defense genes in the host plant which trigger the induced resistance to protect against pathogens. Plant plasma membrane receptors are responsible for sensing pathogen-associated molecular patterns (PAMPs) as per the PAMP-triggered immunity (PTI) process. This triggers signal transduction processes inside the cell which result in defense reactions. The receptor-like protein ELR (Elicitin Response) which mediates the broad-spectrum identification of PAMPs from numerous Phytophthora species is a well-known example of PAMP-triggered immunity (PTI) (Du et al., 2015). Elicitor-triggered immunity is another defensive mechanism (ETI) which suggests that the pathogen possesses effector or elicitor chemicals to facilitate its invasion of the host tissue. These effectors are recognized by the plant defense system and an immune response is activated. This leads to the activation of ETI and results in Reactive Oxygen Species (ROS) production, callose deposition, and programmed cell death through the hypersensitive response (HR) (Turnbull et al., 2019). There are numerous signals shared by the PTI and ETI. However, in an ETI, the immune response is strong and happens faster than in a PTI (Tao et al., 2003).

4.1.2 Disease Resistant Genes

The first attempt at resistance to the disease was made in the mid-19th century, which resulted in 'Field Resistance' that was partially successful (Wastie, 1991). Resistance to late blight is controlled by a few major genes (R genes), which can be easily overcome by new races of *P. infestans* and/or by an unknown number of genes expressing a quantitative type of resistance that may be more durable (Oberhagemann et al., 1999). This resistance is more durable than that mediated by R genes but is difficult to move into cultivated varieties by crossing and phenotypic selection. Wild varieties of potato are a major source of resistance genes (R genes) including Rpi genes against *Phytophthora infestans*. To impart resistance into cultivated potatoes, potato breeders utilize wild genes which are derived from wild germplasm (*S. bulbocastanum*, *S. venturii*, *S. stoloniferum, S. americanum*). There are tuber-bearing species in the Solanum section Petota that may contribute new genes for disease resistance. The identification of dominant resistance genes (Rpi genes) against *P. infestans* in potato wild species has resulted from extensive research on potato late blight (Paluchowska et al., 2022). The major success in the development of resistance in potato late blight was achieved when the immune Rpi gene was derived from the wild tuber species *Solanum demissum* with genes R1-R11 (Black et al., 1953, Malcolmson and Black,, 1966). Recurrent backcrossing of *Solanum demissum* to var of *S. tuberosum* is used to transfer late blight resistance. Many varieties carry the R1 gene, whereas others carry R2, R3, and R4. However, the R gene provides only transient resistance to late blight by encoding receptors that recognize secretory effector (Avr) proteins produced by *P. infestans* (Akino et al., 2014). According to (Stefańczyk et al., 2017), R gene recognizes effector protein, which triggers hypersensitivity reaction and prevention of infection takes place. Those resistance genes, however, were quickly overcome by other virulent strains of *P. infestans* within 2 to 3 years. It takes time to introduce Rpi genes into commercial cultivars from wild relatives of the potato through crossing, particularly when dealing with species that are separated from the potato and have crossing challenges, such as variable endosperm balance numbers (EBNs) (Paluchowska et al., 2022). Many functional plant nucleotide-binding leucine-rich repeat resistance genes (NLRs) regulate a variety of pathogens (Bendahmane et al., 1999). Rpi genes in plants also belong to the family of NLR genes (Rodewald et al., 2013). The method of diagnostic Resistant Enrichment Sequencing (dRenSeq) has been developed to identify and validate the known functional R genes present in wild species. This technology is used for resequencing of NLRs (Jupe et al., 2013). Marker-assisted selection (MAS) is a valuable tool in the early stages of genotype selection, eliminating the need for pathogen inoculation tests. In a study conducted by (Sharma et al., 2013), markers for resistance genes in both indigenous and exotic potato genotypes were validated. They identified 17 genotypes that possessed a combination of R1, R2, and R3a genes, which are now being incorporated into the Indian breeding program to enhance resistance in a single host background. Somatic hybrids with a high level of resistance to late blight can also serve as potential parents for potato breeding, as highlighted by (Tiwari et al., 2013). A recent study shows there is a more effective gene (Rpi2 gene) that shows resistance to *P. infestans* which was taken from the wild species of *Solanum pinnatisectum* that provides broad spectrum resistance against the various strains of *P. infestans* (Yang et al., 2017). Researchers have been searching extensively to find genes that confer resistance against potato infections, particularly *Phytophthora infestans* (Vleeshouwers et al., 2011). It was recently also hypothesized that the resistance present in JAM 1-4 stemmed from an uncharacterized new resistance gene or genes (Paluchowska et al., 2022).

4.1.3 Use of Disease Resistant Varieties

The use of resistant varieties is one of the main components of late blight control and is particularly effective under tropical conditions (Chowdappa, 2015, Pacilly et al., 2016). Advancements in molecular techniques have facilitated the replication, sequencing, and creation of novel transformed versions of commercially available potato cultivars. The risk of fungicide tolerance to changes in the population structure of *P. infestans* is decreased by resistant cultivars (Tsedaley, 2014, Arora, 2014). To increase tolerance in the genes of native species that have been severely impacted by non-native invading plant pathogens, plant breeders are attempting to create disease-resistant cultivars (Shah et al., 2020). It is always advisable to use resistant varieties even when the fungicides spray is considered as the main control strategy because resistant varieties delay the onset of the disease or reduce its rate of development so that fewer sprays on a resistant variety may be needed to obtain a satisfactory level of control of the disease (Agrios, 2005). The effective *Phytophthora infestans* management has proven a reduction in fungicide inputs on moderately tolerant potato cultivars in comparison to susceptible cultivars (Fry 1978, Gans et al., 1995, Naerstad et al., 2007).

The concept of durable or polygenic resistance is sometimes misconstrued as being synonymous with intermediate levels of resistance. Polygenic resistance has proven to be effective in reducing the need for fungicides (Jones, 1998). Cultivars possessing polygenic resistance exhibit significantly lower values of the Area Under the Disease Progress Curve (AUDPC) compared to susceptible cultivars (Fry, 1978). Additionally, the use of plants with field resistance can impede the growth rates of pathogens. There is a wide range of resistance levels to late blight among commercial potato cultivars which can be incorporated into an overall management strategy (Jones, 1998). Nevertheless, it is important to note that no potato varieties are completely resistant to late blight. While most resistant varieties are not immune to late blight, they do possess varying degrees of resistance to different races of the pathogen (Popokova, 1972). Cultivars with higher levels of resistance require fewer fungicide sprays compared to those with lower levels of resistance (Fry, 1978). Although some released improved varieties have lost their resistance to late blight, there are still some that exhibit better tolerance when supported by reduced doses and rates of fungicide application. Farmers consistently prioritize the demand for late blight resistant varieties to effectively manage the disease (Rana et al., 2011). By combining disease resistance in potato varieties with the use of fungicides, the progression of late blight can be significantly slowed down. Consequently, the cultivation of potato varieties with field resistance to late blight in tubers coupled with a moderate to high resistance in the foliage can help reduce the reliance on fungicides. The management of late blight has benefited greatly from the development of resistant cultivars and the application of screening methodology (Bhardwaj et al., 2005, Joseph et al., 2007, Kaushik et al., 2007, Joseph et al., 2011).

4.1.4 Resistance Induction: Successes and Challenges

Developing resistance in the potato crop to the pathogen appears to be one of the most effective and eco-friendly strategies for controlling late blight. The most important stage in breeding for resistance is identifying genes and loci with possible resistance-conferring abilities to induce durable resistance. The evolution of pathogens to overcome this resistance over time, however, may make this goal difficult to achieve. As a result, more systematic approaches, which may include the use of wild sources to find resistance genes, are constantly needed (Nelson et al., 2018). Genetic engineering techniques like cis genesis allow Rpi genes to be incorporated into commercial cultivars more quickly than they could be through traditional breeding (Ghislain et al., 2019). It has been suggested that inserting multiple Rpi genes at once can prevent a quick overcoming of resistance in recently engineered cultivars (Haverkort et al., 2016). The failure of the "vertical" resistance genes renders the use of fungicides necessary. Breeders look for traits that are marketable, like yield, tuber size, and appearance, because they are aware that fungicides can be used to address late blight disease. It has long been known that introducing R-genes, which only confer race-specific resistance, into cultivated potatoes, derived from wild sources can induce resistance against *P. infestans*; however, new pathogen races have been able to overcome this practice. Thus, long-lasting resistance could be provided by quantitative resistance using multiple genes. Additionally, finding genes linked to host immunity other than R genes can improve methods for disease resistance. While late blight resistance programs face numerous obstacles, a thorough understanding of the pathogen and its host genome holds great promise for future advancements in resistance breeding.

4.2 Biological Control

Biological control is a method of plant disease management that involves inhibiting plant pathogens, improving plant immunity, and/or modifying the environment through the effects of beneficial microorganisms, compounds, or healthy cropping systems. Biocontrol agents utilize microbes and byproducts secreted by the organism to combat a specific plant disease either via hostile reactions or through the development of immunity against them (Jet et al., 2019). Biocontrol mechanisms can be roughly classified into four groups. They are: 1) competition for resources, such as food, water, and/or space, as well as frequently for rare nutrients like iron. Competitive saprophytes are the biocontrol agents that carry out this form of action. Here, in addition to the physicochemical characteristics of the soil that inhibit the growth of disease-causing bacteria, disease suppression by diverse populations of microbes or other organisms in the soil may also take place (e.g., through the action of suppressive soils). 2) Mycoparasitism, in which the plant pathogen (target species) is directly infected and the biocontrol agent is referred to as a facultative hyperparasite. 3) Another characteristic of facultative hyperparasites is antibiosis, in which the prey (plant pathogen) is eradicated by the production of lytic enzymes, poisons, and antimicrobial substances. 4) Induced host resistance, in which a facultative plant symbiont triggers innate immunity or produces plant hormone mimics or precursors to impart resistance to entering pathogens (Jet al., 2019).

The introduction of biocontrol agents' fungi, bacteria, oomycetes, and substances produced by those antagonists can manage late blight in an environmentally friendly manner while addressing ecological imbalance and chemical pollution. Instead of fungicides, bacterial strains (*Pseudomonas fluorescens, Enterobacter cloacae*) can be used as biological control agents (BCA) to inhibit late blight infestation. Use of the fungus *Trichoderma atroviride* for tuber treatment minimizes the tuber rotting problem. It has been demonstrated that *T. harzianum* can continue to grow and colonize the developing potato plant's new stems, stolons, and roots throughout the growing season, preserving its efficacy as a controlling agent and making it a desirable substitute for traditional seed treatments (Harman, 2000, Howell, 2003). During colonization, the antagonistic oomycete *Pythium oligandrum* secretes enzymes that break down cell walls in addition to exhibiting mycoparasitism. Its mycoparasitic abilities allow it to utilize a variety of fungi and oomycetes for nutrition (Liang et al., 2020). Biocontrol potential is also shown by bacteria such as *Streptomyces*, *Pseudomonas*, and *Bacillus*. *Pseudomonas spp.* use volatile organic compounds (VOCs) like hydrogen cyanide and aldehydes to impede *P. infestans* growth, while Bacillus species directly oppose *P. infestans*. Furthermore, some strains of *Pseudomonas* generate cyclic lipopeptides that target siderophores and *P. infestans* zoospores that compete for iron, impeding the growth of the latter (Caulier et al., 2018, Cray et al., 2016). Numerous BCAs generate enzymes that degrade cell walls; their powerful combinations may be employed to choose effective biocontrol agents in the future. A crucial tactic is to target the *P. infestans* cell wall, which is primarily made up of cellulose and β-D-glucans (Liang et al., 2020, Kubicek et al., 2019). Additionally, bacterial bioagents like *Pseudomonas putida* and *Bacillus subtilis*, as well as fungal bioagents like *Trichoderma paraviridicens* and *T. erinaceum,* have shown promise in reducing late blight severity when sprayed multiple times (Islam et al., 2022). Depending on the host, plant, pathogen, and environmental conditions, biocontrol capacity and mode of action are often strain-specific, and the majority of BCAs use multiple modes of action to control pathogens (Jet al., 2019). In vitro assays, together with molecular and genomic research, provide a deeper understanding of the biology and mode of action of BCAs. Research on *Pseudomonas*, for instance, has identified certain loci regulating aggressiveness towards *P. infestans*, raising the prospect of creating hyper-aggressive strains for usage in the future (Vrieze et al., 2020). Furthermore, these investigations can provide insight into the evolutionary background of BCAs, such as the acquired hyperparasitism of *Pythium* via horizontal gene transfer. (Caulier et al., 2018). Biocontrol agents perform well under laboratory conditions, but their field efficiency is quite unstable due to their interactions with various biotic and abiotic factors. Because of the rapid changes in the host's physiology, genetic state, and climatological factors, the bioagent impact is often lower in the farmer's field situation.

4.3 Botanical Control

Non-hazardous and eco-friendly botanical extracts are one of the safest control methods for this pathogen. The botanical control method is discussed in Table 3.

Table 3: Botanical control of *Phytophthora infestans*

S.N.	Description	References
1.	The aqueous plant extract from *Allium sativum* and *Allium indica* at a 30% concentration was found effective in controlling late blight.	(Mehmood et al., 2022)
2.	The extract from garlic cloves totally prevented the production of zoospores at concentrations of 1 or 2% (Wang et al., 2004). The extract of *Inula viscosa* diluted in acetone or water at 1% (W/V) reduced the late blight severity by more than 90% on potato and tomato plants.	(Wang et al., 2004)
3.	The essential oils acquired from *Origanum syriacum* var. *bevanii*, *Thymbra spicata* subsp. *spicata*, *Lavandula stoechas* subsp. *stoechas*, *Rosmarinus officinalis*, *Foeniculum vulgare*, and *Laurus nobilis* have an anti-oomycete activity that induces sporangiophore morphological alterations that are degenerative and prevent the development of sporangia.	(Soylu et al., 2006)
4.	Azadirachtin, an active component, is present in neem oil and extracts at higher levels and has been employed to inhibit *P. infestans* from growing.	(Rani et al., 2006)
5.	An assessment of antifungal efficacy from extracts of five distinct plants: *Brassica nigra*, *Cinnamomum camphora*, *Melia azedarach*, *Eupatorium adenophorum*, and *Lantana camara* was conducted against the *P. infestans* fungal isolates. *Brassica nigra* was found to be the most potent to limit the disease	(Maharjan et al., 2010)
6.	The ability of six plant extracts (*Galla chinensis*, *Potentilla erecta*, *Rheum rhabarbarum*, *Salviae officinalis, Sophora flavescens*, and *Terminalia chebula*) to inhibit *Phytophthora infestans* infection on detached potato leaves, seedlings, and tuber slices was investigated. *G. chinensis* was the best on detached leaves and *R. rhabarbarum* exhibited the strongest inhibitory impact on seedlings	(Shutong et al., 2007)
7.	The leaf extracts from onions, garlic, Malustoringo, *Reynoutria japonica*, and *Rheum coreanum* showed positive inhibition of *P. infestans* mycelial growth out of 100 species in 54 plant families tested against the fungus. Extracts from *M. toringo* effectively controlled late blight and showed substantial inhibition of *P. infestans.*	(Paik, 1989)
8.	The compound Serenade controlled the growth of mycelium of *P. infestans*. The water extract of *S.candadensis* at 1 to 5% concentration was effective on controlling the pathogen. The same kind of effect was shown by the extracts of *R. rhabarbarum* and Elot-Vis when used at 5% concentration.	(Stephan et al., 2005)
9.	5% (w/v) of crude aqueous extract of the leaves of *Syzygium cumini*, *Psidium guajava*, *Eucalyptus globusus*, and *Carica papaya*; fruits of *Termininalia bellirica*, *T. chebula*, and *Piper nigrum*; flower buds of *Syzygium aromaticum*, and cloves of *Allium sativum* were tested. Among the 10 botanicals tested, the extract from the leaves of *Syzygium cumini* was found to be the most efficient in reducing the incidence and severity of late blight disease up to 66 DAS (days after sowing), and it also boosted potato output by 71.29% when compared to the untreated control.	(Islam et al., 2021)

4.4 Physical Method

Physical techniques such as heat, radiation, hot water, hot steam, and solar energy have proven to be efficacious in diminishing the inoculum of *Phytophthora infestans* within the soil (Scagel et al., 2023). An illustration of this is the immersion in water at a temperature of 44°C for a duration of 5 minutes, which leads to a notable reduction in the viability of *P. infestans* isolates (Lalaymia et al., 2022). Another successful method is soil solarization achieved through the utilization of transparent plastic mulches, which effectively eradicates the pathogen's inoculum (Abdelrahman et al., 2022). Soil solarization by heat, hot water treatment of propagative organs, elimination of desirable wavelengths of light for pathogens to inhibit growth, and refrigeration of tubers are some common physical ways used in farm situations to control *Phytophthora*.

4.5 Cultural Practices

Cultural practices are the first line of defense against late blight (Arora et al., 2014). The main objective of cultural management of late blight disease is the creation of a favorable environment for crops and an unfavorable environment for pathogens with appropriate cultural practices from site selection to tuber harvest. Cropping, intercropping, weeding, and field sanitation are examples of cultural practices that can significantly reduce the pathogenic infestations of crops (Tripathi et al., 2020). Cultural practices can be utilized to decrease the population of the pathogen by reducing its survival, reproduction, dispersal, and penetration. To minimize the survival of *P. infestans* and prevent the initiation of an epidemic, it is important to avoid introducing late blight into a field by planting disease-free seed tubers, preferably certified seed. The most successful strategy for managing late blight is to prevent the introduce of inoculum. The primary sources of inoculum are likely to be infected potatoes in cull piles, infected volunteer potato plants that have survived the winter, and infected seed tubers. Therefore, it is crucial to maintain a clean operation by destroying all cull and volunteer potatoes (Agrios, 2005). Additionally, frequent or night-time overhead irrigation should be

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avoided and good soil coverage should be maintained (Draper et al., 1994). Irrigation is an essential component of managing late blight disease. The pathogen *Phytophthora infestans* causes tuber infection if soil moisture levels exceed field capacity for a minimum of 24 hours and are then followed by at least 8 mm of rainfall (Adams and Stevenson, 1990). Effective control of late blight involves eliminating cull piles and volunteer potatoes, implementing proper harvesting and storage practices, and applying fungicides when necessary (Davis et al., 2009). Careful selection of seed sources is also important to avoid introducing late blight on seed, particularly new strains of the pathogen (Kirk, 2009). In cases where partially blighted leaves and stems are still present at harvest time, it is necessary to remove the aboveground parts of potato plants or eliminate them using chemical sprays (herbicides) or mechanical methods to prevent the tubers from becoming infected. Regularly inspecting all stored potatoes and promptly removing any diseased tubers from storage is highly recommended to prevent the spread of diseases (Stone, 2009). Excessive irrigation and fertilizer applications should be limited during the late season. Additionally, it is advisable to kill the vines at least two weeks before harvest. After vine killing, it may be beneficial to spray the foliage with approved fungicides to eliminate any remaining late blight spores (Kirk et al., 2013). Harvesting should be managed in a way that minimizes tuber damage. If the tubers are stored after harvest, they should be completely dry before being placed in storage, and the temperature and humidity of the storage area should be carefully regulated (Kirk, 2009).

4.6 Chemical Management Approaches

Chemical fungicides applied at appropriate rates and intervals based on the severity of the disease and the climate are an efficient way to manage potato late blight (Majeed et al., 2014). The application of fungicides is an efficient way to stop late blight as soon as possible but there are significant agricultural issues with public health, environmental concerns, and associated expenses (Majeed et al., 2014, Majeed et al., 2017). Fungicide spray is the most common management practice of late blight disease. Several studies have highlighted the effectiveness of distinct chemical fungicides in the control of late blight. Investigations have demonstrated that fungicides such as Krilaxyl Gold, Milraz, Ridomil, and Mistress 72 have the ability to significantly mitigate late blight severity and enhance potato yields through application at designated time intervals (Adhikari et al., 2023). Over $3 billion is thought to be spent annually on fungicides that treat late blight worldwide (Haverkort et al., 2008). Many chemicals have been produced to control different plant diseases by stopping or eliminating the microorganisms that cause the disease and understanding these chemicals is crucial to minimizing production losses (Tiwari et al., 2020). Fungicides used on time will slow down or prevent new symptoms but they won't cure the symptoms of late blight. Traditionally, controlling late blight mostly depends on applying a preventive fungicide on a calendar based schedule during the growing season. The discovery of the Bordeaux mixture, a first-generation fungicide in 1885 was an important milestone in the history of chemical disease control (Liu et al., 2017). The widespread and uncontrolled application of these chemicals not only endangers the environment but also poses a significant risk to human health. Together with other pesticides, late blight fungicides are one of the main causes of pollution in the air, soil, and water and can be extremely dangerous to children, farmers, and non-target animals. But Metalaxyl, a fungicide belonging to the oomycetes-specific phenylamide group fundamentally altered how late blight was managed (Bruck et al., 1980). Its use immediately increased due to its success making it one of the fungicides that is most commonly used worldwide. Cymoxanil mixtures have been proven to be efficient for the treatment of *P. infestans* strains that are resistant to metalaxyl (Samoucha and Cohen, 1988). Different fungicides have been evaluated for their efficacy in managing late blight. For example, the combination of azoxystrobin and tebuconazole, sprayed at a rate of 1 ml/liter of water, is effective in reducing the incidence of late blight and increasing yield and net income (Singh and Mer, 2023). Other fungicides such as Propineb, Cymoxanil, Metalaxyl, and Mancozeb have also been used in alternate spray intervals to manage potato blight and improve net farm returns (Kilonzi et al., 2022). The choice of fungicide and its application frequency can have a significant impact on the quality of tubers and overall potato yield.

Unfortunately, continuous mass application of fungicides causes increased evolutionary pressure on *P. infestans* and consequently may initiate rapid adaptation and acquisition of resistance to a fungicide involved (Wang et al., 2018). *P. infestans* might become resistant to seven different fungicides in a single season when potato crops were treated in the field with them (Grünwald et al., 2006). There are three primary phases in the development of fungicide resistance: emergence, selection, and adjustment. The resistant strain needs to arise through invasion and mutation during the emergence phase. The pathogen population contains the resistant strain during the selection phase, and a tiny fraction of the pathogen population that carries the resistance grows as a result of the fungicides' selective pressure. The resistant portion of the pathogen population increases significantly throughout the adjustment period (Van Den Bosch et al., 2011). Two major categories of compounds have been used regularly: protectants (such as dithiocarbamates, triphenyl tin hydroxide, and chlorothalonil) and systemic fungicides (such as metalaxyl/mefenoxam, phenylamides, and aliphatic nitrogen fungicides like cymoxanil, as well as morpholine fungicides like dimethomorph). Due to the pathogen's populations developing resistance to the phenylamide fungicide metalaxyl and the widespread emergence of new virulent genotypes, the disease has spread to epidemic proportions in North America, Russia, and Europe (Drenth et al., 1994, Grinberger et al., 1995). Some researchers have recently argued that cisgenesis, a particular type of genetic modification, would require a less stringent assessment because it is safer and more socially acceptable.

5. FORECASTING MODELS FOR LATE BLIGHT MANAGEMENT

Forecasting models are science-based tools implemented as a support system since it is more difficult to make rational decisions about disease management due to the complexity of interconnections between several elements that impact the incidence and progression of disease. These models utilize various meteorological parameters to predict the occurrence and severity of late blight, thereby assisting farmers in decision-making regarding fungicide application timing (Henderson et al., 2007). Computer-based forecasters can integrate and organize available information on the pathogen, the influence of observed and forecast weather on the disease, cultivar resistance, fungicide characteristics, and efficacy required to make general or site-specific decisions concerning the management of late blight. Forecasting also assists in chemical control by providing relevant information about the spray, its amount, timing, and frequency of application. There were some practices to predict the time of the first application of fungicide spraying and the timing for subsequent application, which helps to reduce the number of sprays needed and broad accessibility to effectively manage blight (Litschmann et al., 2020). Forecasting of disease allows the prediction of the probable outbreak by assessing the presence or absence of favorable climatic parameters for disease progress. The correlation of the progression of phenological stages with thermal time (GDD and P-days) indicated that lower maximum temperatures and accumulated growing degree-days were associated with higher concentrations of *Phytophthora infestans*, highlighting the significance of temperature in forecasting late blight risk in potato crops (Seijo-Rodriguez et al., 2018). Over the years, several concepts have been developed and used to predict potato late blight worldwide. These include ‘Dutch rules’, Beaumont's periods, Irish rules, the moving day's concept, severity value accumulation, negative prognosis, mathematical models, and more. While the rules were generally found to be satisfactory, occasionally the blight would appear even when the "Dutch rules" were not fulfilled. This rule was used for successful forecasts of late blight under conditions in the UK. Some recent and major forecasting efforts and models are discussed in Table 3.

Table 4: Recent and major forecasting efforts and models

S.N	Forecasting based on specific rules or forecasting models	Developed in/by	Input characteristics and description of the model	References
1.	Forecasting based on CARAH rule	Developed by l'Agronomie et l'Agro-Industrie du Hainaut (CARAH)	Forecast the occurrence of potato late blight (PLB) incidence in mountainous regions using meteorological estimation mainly relative humidity based on CARAH rules, achieving average errors of 1.17°C and 8.0% for air temperature and humidity, respectively.	(Wu et al., 2023)

Table 4 (Cont.1): Recent and major forecasting efforts and models

2.	Deep learning classification particularly the Blight LSTM-AE model	Abderrahmane et al.'s research in 2022 in North-Western Algeria.	Predicts the early late blight outbreaks up to 30 days in advance by incorporating temperature data.	(Abderrahmane et al., 2022)
3.	Naerstad Model	Hjelkrem et al in 2021 in Norway	Incorporates 19 uncertain parameters including spore production, release, survival, and infection of *Phytophthora infestans* in addition to requiring hourly weather data inputs such as air temperature, precipitation, relative humidity, global radiation, and leaf wetness for accurate prediction of late blight, particularly for susceptible cultivars like Bintje and Saturna.	(Hjelkrem et al., 2021)
4.	Forecasting based on Modified Irish Rules	Cucak et al in 2019	Evaluated the 'Irish Rules' potato late blight forecasting model and proposed systematic adjustments to improve its accuracy and reduce pesticide inputs. Through empirical analysis, they recommended revisions to relative humidity and duration thresholds, challenged previous temperature assumptions, and proposed dynamic decision thresholds based on disease outbreak frequency, offering a comprehensive methodological framework for ongoing model re-evaluation and optimization.	(Cucak et al., 2019)
5.	BLITE-SVR (support-vector regression) Model	Gu et al in 2016 in South Korea	Forecasts late blight on potatoes utilizing support-vector regression(SVR), which demonstrated higher accuracy (64.3%) in predicting the first date of occurrence compared to conventional methods like moving-average, pace regression, and linear regression.	(Gu et al., 2016)
6.	Artificial Neural Network (ANN) model	Baker et al in 2014 in Michigan	The grid-trained artificial neural network model demonstrated better accuracy on days with late blight risk, it required retraining using newly available data sources, highlighting the importance of adaptation to evolving weather datasets for improved decision support system performance.	(Baker et al., 2014)
7.	BLITECAST	Krause and Associates at Pennsylvania State University	-Traditional forecasting model based on the average temperature over 5 days and the cumulative rainfall over a 10-day period. Through a phone call to a computer at the forecasting center, Pennsylvania State growers could pass on meteorological data collected in potato fields to receive recommendations.	(Krause et al., 1975)
			-The primary draw of this centralized disease forecasting system was the recommendations that it provided to the growers.	(Singh and Shailbala 2012)
8.	NegFRy Model	Developed in Denmark	Predicts late blight appearance based on weather thresholds of 270 ratings reaching within 15 days.	(Singh and Shailbala 2012)
9.	JHULSACAST	Developed by the Central Potato Research Institute (CPRI) and the University of Florida	-Crop simulation model which forecasts the occurrence and severity of potato late blight disease based on weather data and crop growth parameters.	(Jagyasi et al., 2015)
			-This model successfully forecasted late blight well in advance compared to other tested forecasting models.	(Jagyasi et al., 2015)
			-The main difference between this JHULSACAST model and the BLITECAST model is that the BLITECAST is designed to predict the onset of late blight.	(Krause et al., 1975)

Table 4 (Cont.2): Recent and major forecasting efforts and models

10.	CHINA BLIGHT	Developed by Chinese researchers in the form of a web-based Decision Support System	-Provides real-time distribution of potato late blight, infection risk assessment based on weather data, and a farm-based DSS for chemical control.	(Hu et al., 2012)
			-It has included knowledge information and services like control methods on late blight, Resistance of cultivars, Fungicide database, Other pests on potatoes, Questions and experiences exchange, and Electronic records for field practices of users.	(Hu et al., 2012)
11.	PhytoPRE + 2000	Developed in Switzerland	This improved system incorporates weather conditions during the major infection and sporulation period (MISP) .	(Cao et al., 1996)
12.	ProPhy	Developed in the Netherlands	-The first fungicide spray should be applied when the crop reaches a height of 15 cm for vulnerable types and ten days later for moderately resistant cultivars.	(Schepers, 1995)
			-Compared to other models for comparable disease control, this model employed fewer spray recommendations.	(Nugteren, 1997)

6. FUTURE PROSPECTS AND CHALLENGES

At Massachusetts Institute of Technology in Cambridge, the Broad Institute is sequencing the whole genome of *P. infestans* (Van Den Bosch et al., 2011). A better-educated approach to the generation of more resilient resistance will be made possible by the pathogen's complete genome sequence and the mapping of host resistance genes in potatoes and tomatoes. One day, potato types that are both pathogen-resistant and agriculturally desirable to the producer may be developed by an understanding of the avirulence genes in the pathogen that trigger defense responses in the host (Jiang et al., 2005). Undoubtedly, diverse strategies include knowing the pathogen's historical and current populations through molecular methods, testing pathogen populations for fungicide sensitivity, and comprehending host resistance mechanisms and how pathogen populations adapt to get around them. Modern scientific methodologies have the potential to produce genetically modified marker-free potato varieties (trans- or cisgenic, the latter indicating the utilization of indigenous resistance genes) as enhanced versions of presently available varieties exhibiting significantly higher resistance levels (Haverkort et al., 2008). The process of domestication has diminished the inherent ability of potato plants to combat pests and diseases, thus making them vulnerable to diseases like late blight caused by Phytophthora infestans (Dufkova et al., 2023). Attempts have been made to create potato cultivars that are resistant to late blight, but the outcomes have been limited, resulting in the extensive use of fungicides in potato production (Gopal, 2023). In addition to genetic methods, biotechnological techniques such as genome editing and genetic transformation have exhibited the potential to produce potato plants that possess long-lasting resistance against pathogens (Orchard et al., 2023). In summary, a combination of genetic and biotechnological approaches can aid in the development of more robust and disease-resistant potato cultivars. To create such improved varieties, significant scientific investments are required, but the effects these varieties will have on the economy and environment will be significant. The near future may see the identification, isolation, and pyramiding of novel gene sources possessing long-lasting resistance against *P. infestans* into potato through the application of effectoromics, transcriptomics, metabolomics, and cis-genic methodologies.

Future research should prioritize the development and implementation of robust forecasting models applicable across diverse regions and climates. These endeavors are aimed at enhancing accuracy, bolstering early warning systems, fostering global collaboration for data sharing and expertise exchange, and integrating with precision agriculture to optimize resource utilization and mitigate environmental impact and input costs. To achieve these goals, employing advanced tools such as sophisticated data collection systems (e.g., satellite imagery, remote sensing, weather stations), modeling techniques (e.g., numerical weather prediction models, compartmental disease epidemiological models), and data analysis and improving tools (e.g., machine learning, artificial intelligence, geographic information systems, disease surveillance networks, mobile/web-based decision support systems, crowd sourcing) is imperative. However, numerous challenges hinder these objectives. First, accessing high-quality data on weather, crops, and diseases is paramount. Second, the intricate dynamics of diseases, such as late blight, pose challenges in algorithmic incorporation due to multifaceted influences including weather conditions, host susceptibility, pathogen strains, and agronomic practices. Third, climate change exacerbates these challenges by altering weather patterns, necessitating model adaptability. Fourth, validating models against real-world data and gaining acceptance from stakeholders, particularly farmers and policymakers, is arduous. Therefore, user-friendly communication of model predictions and uncertainties is imperative for trust building and adoption. Fifth, ethical and social considerations, such as equitable technology access, privacy concerns, and impacts on small-scale farmers, warrant attention. Addressing these challenges will require interdisciplinary collaboration among scientists, policymakers, farmers, and other stakeholders to develop robust forecasting models that effectively manage late blight while considering broader societal implications.

7. CONCLUSION

Late blight of potato is the most costly and yield reducing disease of potato. As long as *P. infestans* is not eradicated, agriculture will continue to suffer greatly from it. The pathogen thrives in cool, humid environments, which can lead to serious disease outbreaks and significant crop losses. Different methods of management can be used to treat potato late blight such as the use of resistant varieties, disease-resistant genes, intercropping, biological control agents, certified disease-free seed, selective fungicides, cultural practices like deep-burying or freezing cull piles, as well as destroying volunteer potato plants in neighboring fields. The only effective way to avoid late blight at the present time is the use of chemical fungicides, but this has negative effects on the environment, the public health, and the economy. Due to high cost and regulatory restrictions, the most advanced and selective techniques for precisely controlling gene function with RNA interference have not yet found widespread use in agriculture. Therefore, using integrated disease control techniques is required to overcome these challenges. By using DSS, fungicide applications may be timed more effectively and the dosage of the fungicide can be changed in response to infection pressure and cultivar resistance. Through extension officers, phone, fax, email, SMS, PC, and websites on the Internet, DSS can provide consumers with generic or very site-specific information. Databases and online tools have emerged as the primary distribution channels over the Internet. Using resistant cultivars, controlling key inoculum sources, and employing dynamic fungicide dosages based on weather forecasts are expected to be the most crucial components of future integrated late blight management strategies.

CONFLICT OF INTEREST

There is no known conflict of interest. All the authors have approved the final version of the manuscript.

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