



E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(6): 594-601
Received: 17-04-2026
Accepted: 22-05-2026

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Integrated disease management approaches for late blight of potato caused by *Phytophthora infestans*: A concise review

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i6h.5751>

Abstract

Potato (*Solanum tuberosum* L.) is a vital food crop threatened by late blight caused by *Phytophthora infestans*, which rapidly spreads and adapts, causing significant yield losses. Effective management requires integrated strategies including crop rotation, use of clean seed tubers, field sanitation, and careful application of fungicides amid rising resistance. Biological control agents and breeding for resistant varieties, enhanced by tools like CRISPR/Cas9, offer promising solutions. Disease forecasting models, such as JHULSACAST, help optimize control measures. Sustainable late blight management depends on combining chemical, biological, and genetic approaches through collaborative research and farmer engagement.

Keywords: Epidemiology, Management, Pathogen, *Phytophthora infestans*, Potato

1. Introduction

The potato (*Solanum tuberosum* L.), a vital global crop from the Solanaceae family, is valued for its nutrition, economic importance, and adaptability. It ranks fourth after corn, wheat, and rice in global production, with major growers including China, Russia, and India. In India, nearly 2.32 million hectares produce over 56 million metric tons annually, with Uttar Pradesh leading at 19.17 million tonnes. Potatoes provide energy-rich starch, vitamin C, potassium, and fiber, consumed widely across diverse climates and soils. Late blight, caused by the oomycete *Phytophthora infestans*, poses a severe threat to potato and tomato crops worldwide, causing significant yield losses and economic damage. Historically, it triggered the Irish Potato Famine (1843-1845). Current yield losses from late blight are highest in Sub-Saharan Africa (44%), followed by Latin America, Southeast Asia, and others. In India, losses average 10-15%, with some regions experiencing up to 85% crop damage depending on variety susceptibility and environmental conditions.

Effective potato farming requires good soil, crop rotation, certified seed tubers, and integrated disease management (IDM). IDM combines cultural, biological, chemical controls, and resistant varieties for sustainable blight control. Breeding and biotechnological advances, including maintaining genetic diversity, are essential to enhance resistance and yield.

This review provides a comprehensive overview of late blight biology, disease dynamics, and management strategies.

1.1 Biology and Epidemiology of *Phytophthora infestans*

Late blight in potatoes, caused by *Phytophthora infestans*, produces characteristic symptoms on leaves, stems, and tubers, as illustrated in Figures 1 to 3. Initial signs typically appear as pale green to dark brown, water-soaked spots, often near leaf tips and edges. These lesions rapidly grow into large, brown to purplish-black necrotic areas and are usually the first visible indicators of infection (Fry, 2008) [20]. When environmental conditions are conducive, the disease progresses quickly, causing widespread blight that can destroy entire leaves or plants, giving them an appearance ilar to frost injury (Grunwald and Flier, 2005). In moist conditions, a white, downy growth develops on the undersides of leaves, particularly along the borders of dead

tissue, signaling active sporulation (Fry and Goodwin, 1997) ^[21]. Stems may develop dark brown to black elongated lesions; although less frequent than leaf infections, they can girdle the stem and result in plant death during severe outbreaks (Haverkort *et al.*, 2009) ^[29]. On tubers, the disease causes irregular, sunken areas with a brown to purple discoloration (Fry, 2008). When cut open, infected tubers reveal reddish-brown to dark brown granular decay extending inward from the skin (Grunwald and Flier, 2005). Affected tissue is typically firm, dry, and discolored, clearly distinct from healthy parts. These damaged tubers are also vulnerable to secondary bacterial infections, which can lead to soft rot and further deterioration both in the field and during storage.

Host range

Phytophthora infestans is widely recognized for causing significant damage to several crops, especially those in the Solanaceae family. While its host range is limited, it primarily targets potatoes (*Solanum tuberosum*) and tomatoes (*Solanum lycopersicum*), serving as the main pathogen responsible for late blight (Fry and Goodwin, 1997; Nowicki *et al.*, 2012) ^[46, 21]. Nevertheless, under specific environmental conditions, this pathogen can also infect other solanaceous species such as brinjal (eggplant) and chili peppers, resulting in further agricultural losses.

2. Etiology and biology of phytophthora infestans

Phytophthora infestans, the organism that causes late blight, is believed to have originated in Central Mexico (Zimnoch-Guzowska *et al.*, 2003). Its mycelium grows inside host tissue

and consists of transparent, coenocytic hyphae that branch extensively and spread between plant cells. These hyphae produce ple or double club-shaped structures called haustoria, or haustoroid extensions that penetrate host cells. The sporangiophores are thick-walled and segmented, with lateral branches that display periodic bulbous swellings—sites where sporangia form. Sporangia themselves are multinucleate, thin-walled, and translucent, typically oval, pear-shaped, or lemon-shaped, each bearing a noticeable apical papilla. From this papilla, biflagellate zoospores mobile spores are released directly from the sporangia. Cooler conditions promote zoospore production, whereas warmer temperatures encourage direct germination via germ tubes. The pathogen's high variability leads to the frequent appearance of new pathogenic strains, complicating disease management in agriculture. Additionally, sectoring within fungal ies, commonly seen in lab cultures, adds further complexity. Early work by Giddings and Berg (1919) ^[22] and Berg (1926) ^[5] played a key role in identifying genetic and phenotypic diversity within *P. infestans* populations.

Table 1: Losses of Potato due to late blight disease

Name of country	Crop losses (%)	References
India	10-75	Dutt, 1979
Pakistan	50-70	Lal <i>et al.</i> , 2018
Nepal	20	Sharma and KC, 2004
U.S.A	70	Teng and Bissonnette, 1985
Ethiopia	72	Selvaraj, 2013
Kenya	80	Nyankanga <i>et al.</i> , 2004
England and Wales	75	Large, 1958

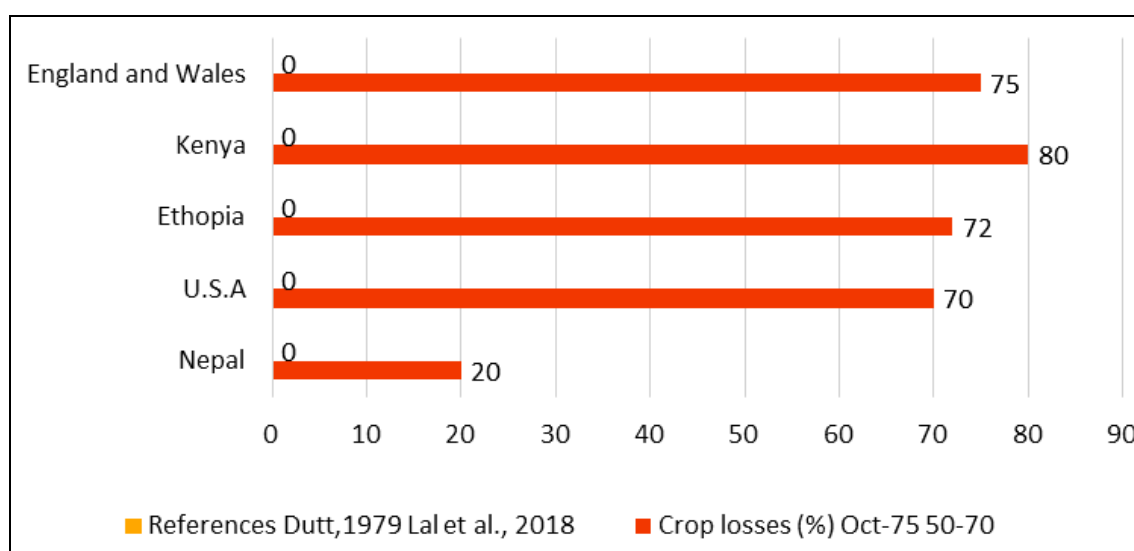


Fig 1: Losses of Potato due to late blight disease

3. Taxonomy and life cycle

Phytophthora infestans is classified within the Oomycetes, a group of fungus-like organisms characterized by intricate life cycles (Fig. 4) that involve both asexual and sexual phases (Judelson, 1997) ^[31]. During asexual reproduction, the pathogen produces sporangia that, under favorable conditions, release motile zoospores. These zoospores can swim through water films, encyst on surfaces, and then germinate to invade host plant tissues. When environmental conditions are conducive, this asexual cycle can repeat several in a single week, enabling swift

disease spread (Nowicki *et al.*, 2012) ^[46]. Sporangia typically survive between growing seasons within infected host tissue, though their persistence in soil or dead organic material remains poorly understood. The frequent repetition of the asexual cycle allows for multiple infection events during one growing season (Drenth *et al.*, 1995) ^[16]. Sexual reproduction takes place when isolates of opposite mating types A1 and A2 interact, resulting in the formation of oospores. These thick-walled structures can remain viable in soil and plant debris for long periods, acting as a primary source of inoculum in future seasons (Judelson, 1997).

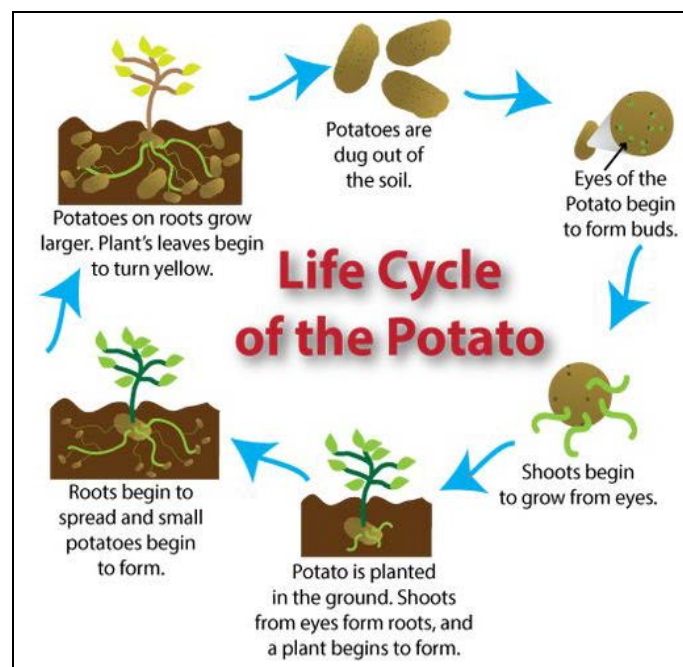


Fig 2: Life cycle of the potato

4. Disease cycle and epidemiology

The infection cycle of *P. infestans* starts when sporangia or zoospores come into contact with potato leaves, stems, or tubers. Given suitable environmental conditions, these spores germinate and enter plant tissue through natural openings like stomata or through injuries. Inside the host, the pathogen spreads between cells and forms haustoria specialized structures that draw nutrients from living plant cells. This process causes cell death and produces the typical signs of late blight, such as water-soaked spots on foliage, stems, and tubers (Birch and Whisson, 2001) [6]. In areas where soil temperatures stay under 30°C, the pathogen can survive between seasons as inactive mycelium in tubers left in fields. When seed tubers are stored in cool conditions, any infected ones become a main source of inoculum for the following crop. *P. infestans* depends on living plant material to persist, including seed tubers, discarded potatoes, volunteer plants, other solanaceous hosts, and even infested soil

(Shinners *et al.*, 2003; Kirk *et al.*, 2013) [33, 55]. The organism is highly adaptable and capable of fast spread when conditions are favorable. Initial dispersal typically happens via airborne sporangia, rain splash, or human-assisted movement of infected material (Fry, 2008) [20]. Secondary infections occur when new spores from diseased plants reach healthy ones, fueling ongoing outbreaks. Environmental conditions play a major role in disease development. Sporangia formation and zoospore release thrive in high humidity (over 90% RH), rainfall, and temperatures between 15 and 25°C. Extended periods of leaf wetness are essential, as they enable zoospores to move, settle, and encyst on plant surfaces (Harrison, 1992) [28]. Tuber infection levels are strongly linked to rainfall during foliar sporulation. The highest rates of tuber infection occur with frequent, heavy rains, especially once about half the leaf canopy is affected (Arora *et al.*, 1987) [3].

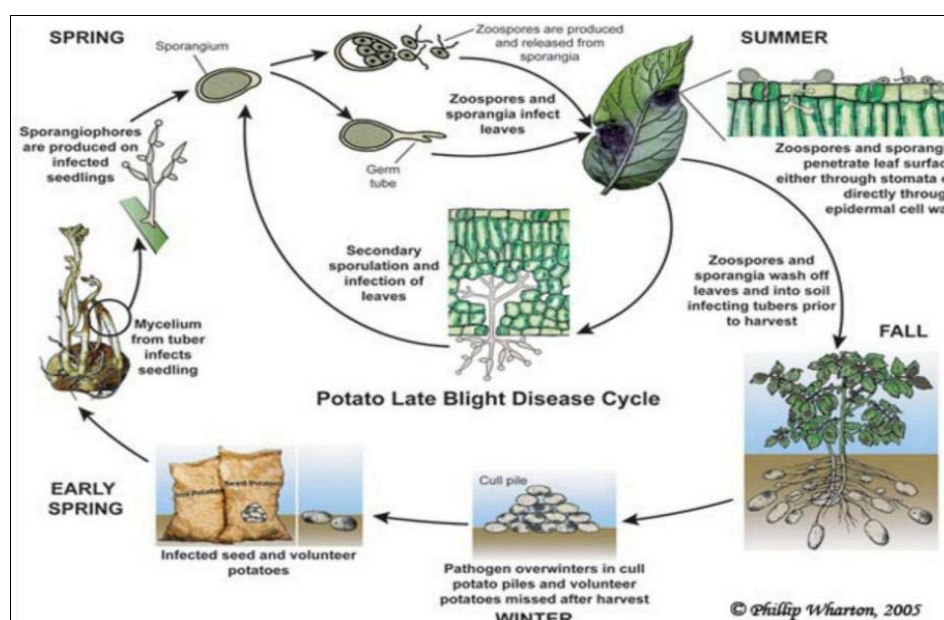


Fig 3: Seasonal Life Cycle of Potato Late Blight Disease (*Phytophthora infestans*) and Its Epidemiological Progression across spring, summer, and fall

5. Host-pathogen interactions

Potato plants can be affected by late blight at any stage of growth, though the greatest vulnerability occurs during tuber development. The disease manifests as water-soaked spots that quickly enlarge, causing widespread tissue breakdown. Affected tubers develop a distinct brown, grainy rot that extends deep into the flesh, making them unsuitable for sale (Crosier, 1934). The relationship between *P. infestans* and the potato involves intricate molecular communication. The pathogen releases effector proteins that alter host cell functions, promoting infection and dampening the plant's immune defenses (Bos *et al.*, 2009). These effectors are introduced into plant cells through

specialized structures called haustoria. In turn, the plant has developed multiple defense strategies to identify and resist invasion. These include pathogen recognition receptors (PRRs) that respond to common microbial features, initiating basic immune responses (Kamoun *et al.*, 1999). Some plants also carry resistance (R) genes capable of detecting specific pathogen effectors, which activates a stronger immune reaction known as effector-triggered immunity (ETI) (Jones and Dangl, 2006). Nevertheless, due to the high genetic diversity of *P. infestans*, the pathogen can rapidly evolve, bypassing plant resistance and giving rise to new, more aggressive strains.

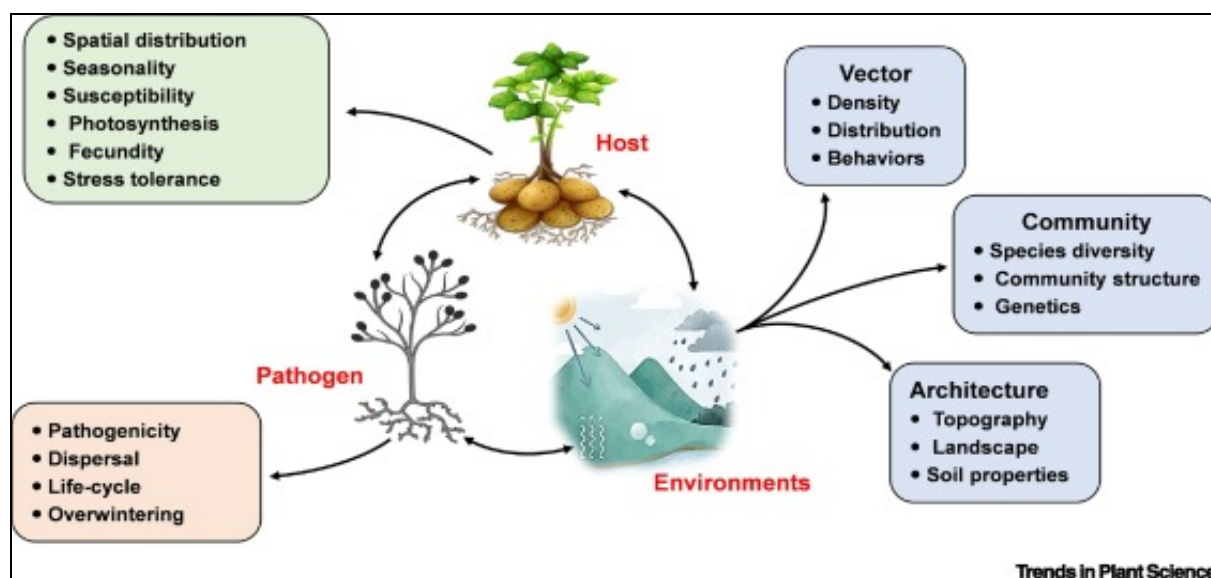


Fig 4: Conceptual Framework of Biotic and Abiotic Drivers of Plant Disease

6. Cultural practices

Cultural practices play a crucial role in controlling late blight, with effective strategies including crop rotation, removal of volunteer plants, and maintaining clean field conditions to limit initial infection sources. To reduce leaf moisture and lower disease risk, it is recommended to avoid overhead or nighttime irrigation and to promote sufficient airflow around plants (Draper *et al.*, 1994) [15]. Planting pathogen-free seed potatoes and ensuring appropriate spacing between plants can further help curb disease spread (Stevenson *et al.*, 2007) [62]. Comprehensive management also includes disposing of cull piles and volunteer potatoes, using sound harvesting and storage methods, and applying fungicides when needed (Davis *et al.*, 2009) [13]. Studies by Bodker *et al.* (2006) [7] and Hannukkala *et al.* (2007) [26] show that rotating potato crops with intervals of three or more years significantly decreases the likelihood of soil-based infections caused by *Phytophthora infestans*.

7. Chemical control of Late Blight

Fungicides continue to play a critical role in managing late blight, a severe potato disease caused by *Phytophthora infestans*. Commonly used protectant fungicides, including chlorothalonil and mancozeb, are applied preventively. These multi-site inhibitors work on the leaf surface to block spore germination and entry into plant tissue. Their broad mode of action targeting several biochemical processes ultaneously makes the development of resistance less likely. Alongside these, systemic fungicides such as metalaxyl are also frequently used (Table 2). These compounds are taken up by the plant and move upward through the tissues, offering curative and even eradivative

effects against existing infections, which is especially beneficial during disease outbreaks.

However, widespread reliance on metalaxyl has led to the emergence of resistant pathogen strains across the globe, including in India (Arora *et al.*, 2014) [4]. Resistance typically arises when repeated applications of single-site fungicides favor mutants that either reduce the fungicide's binding ability or increase its breakdown within the pathogen. When such resistant populations become dominant, previously effective treatments fail, often resulting in significant crop damage.

8. Biological Control of Late Blight

Biological control offers a practical alternative to chemical fungicides in managing *Phytophthora infestans*, the pathogen responsible for potato late blight. A number of antagonistic microorganisms such as species from the genera *Trichoderma* and *Bacillus* have proven effective in suppressing this damaging disease. These biocontrol agents function through various strategies: they may outcompete the pathogen for resources and space, produce substances that inhibit its growth, or stimulate the plant's own defence mechanisms.

For instance, *Bacillus subtilis* strain B5 has been tested using dual culture methods and shown to inhibit the growth of *P. infestans* (Ajay and Sunaina, 2005) [2]. Other microbes, including *Pseudomonas fluorescens*, *Pseudomonas* sp., *Aspergillus flavus*, *A. niger*, *Penicillium* sp., *Trichoderma virens*, and *T. harzianum*, have also been reported to restrict the pathogen's development (Lal *et al.*, 2013) [36]. The diversity of these effective organisms provides a solid foundation for developing commercial biocontrol solutions. Ongoing research

aims to create stable, easy-to-use biological products with consistent performance and longer storage life, enabling their integration into existing crop protection systems (Whipps, 2001)^[66]. When combined with good agricultural practices and

resistant potato varieties, biological control can reduce dependence on synthetic fungicides, delay the emergence of resistance, and promote more sustainable potato farming.

Table 2: Doses of fungicides used to control late blight disease in potato crop.

Trade name	Common name	Doses	Reference
Dithane M-45, Indofil	Mancozeb 75% WP	2.0 Kg/ha	Mekonen and Tadesse, 2018)
Ridomil	Metalaxyl 25%WP	2.5 Kg/ha	(Hannukkala <i>et al.</i> , 2007)
Bravo/Kvach	Chlorothalonil 75% WP	1.5 Kg/ha	(Hannukkala <i>et al.</i> , 2007)al.,2007)
Curzate	Cymoxanil 60% WP	2.0 Kg/ha	Hardy <i>et al.</i> , 1995
Motco/Ridomil gold	Metalaxyl 8% +Mancozeb 64%	2.0 Kg/ha	Mekonen and Tadesse, 2018
Curzate M8	Cymoxanil 8% +Mancozeb64%WP	2.0 Kg/ha	Lal <i>et al.</i> , 2018

9. Current research and future directions

Genomics and biotechnology

Progress in genomics and biotechnology is deepening our knowledge of *P. infestans* and how it interacts with potato plants. Sequencing the organism's entire genome has revealed important details about its genetic variation and the mechanisms behind its ability to cause disease (Haas *et al.*, 2009)^[25]. Researchers are now investigating tools such as CRISPR/Cas9 to create potato varieties with enhanced resistance by accurately modifying resistance (R) genes and analysing the factors that contribute to the pathogen's virulence (Vleeshouwers and Oliver, 2014)^[65].

10. Epidemiological modelling

Improvements in epidemiological modelling are strengthening the capacity to anticipate late blight outbreaks and support timely, targeted disease control strategies. At its foundation, disease prediction modelling aims to determine when a disease might first emerge, how quickly it could spread, and how serious it may become, by systematically evaluating data on weather patterns, crop traits, pathogen dynamics, or combinations of these interrelated factors. For potato late blight caused by *Phytophthora infestans*, such models are especially useful because the pathogen's spore production, spread, and infection process are strongly influenced by moisture levels, temperature, and the length of time leaves remain wet.

10.1 Global development of predictive models

Around the world, many models have been developed and applied to forecast potato late blight (Singh *et al.*, 2013). Early efforts include the Beaumont period (1947) in England, the Wallin model (1962) in the U.S., and the well-known BLITECAST system introduced by Krause *et al.* (1975). These typically use meteorological indicators such as relative humidity above 90%, temperatures between 10-25°C, and extended leaf wetness to calculate "severity values" or "infection risk scores." More recent versions go further by incorporating biological aspects of the pathogen like sporangia survival and latent period duration along with host resistance traits and real-time spore monitoring. Together, these advances allow for dependable assessments that guide decisions on whether, when, and which fungicides to apply.

10.2 Integration into Decision Support Systems (DSS)

When embedded in decision support systems, these models help farmers use fungicides more efficiently, cutting down on unnecessary applications while still maintaining effective disease control (Skelsey *et al.*, 2009)^[60]. A typical DSS delivers clear guidance: for instance, "no spray required" during dry spells, "apply protective spray" under moderate risk, or "apply

curative treatment within 48 hours" when risk is high. Field trials show that model-driven spraying can reduce the number of applications by 30-50% compared to fixed calendar schedules, without affecting yield or tuber quality. This leads to lower production costs, less environmental impact, and a slower rise in fungicide resistance.

10.3 Localised models: The case of JHULSACAST

Singh *et al.* (2000) developed a computerised forecasting tool named JHULSACAST tailored to western Uttar Pradesh in India, which has demonstrated effectiveness in predicting local late blight outbreaks. While ilar in concept to BLITECAST, JHULSACAST has a key distinction: it focuses on predicting the initial onset of disease the date when symptoms first appear in a season rather than tracking progression after the disease has already emerged. This early warning function is particularly beneficial in subtropical and tropical regions where the arrival of blight varies widely from year to year, depending on when cool, humid conditions set in.

10.4 Regional adaptation of models

Due to its success, JHULSACAST has been modified for use in other parts of India, including the Tarai region of Uttarakhand and the plains of West Bengal (Pundhir *et al.*, 2014; Chakraborty *et al.* 2014)^[50]. These adaptations involved adjusting model parameters to reflect regional differences in climate such as frequency of fog, dew formation, and daily temperature fluctuations as well as local strains of *P. infestans* (including those resistant to metalaxyl) and commonly cultivated potato varieties with varying degrees of susceptibility. This highlights an important point: although modelling frameworks can be shared across regions, they must be fine-tuned and validated locally to ensure accuracy.

11. Future outlook

Looking forward, late blight modelling is evolving toward integration with remote sensing technologies—such as satellite and drone-based vegetation indices—real-time spore detection using molecular or immunological methods, and machine learning techniques capable of analysing complex, nonlinear relationships among multiple variables. Mobile platforms—like apps that automatically pull local weather data—are making these advanced tools accessible even to small-scale farmers. When paired with farmer training programs and localised weather monitoring networks, these models become powerful tools for sustainable disease management, reducing chemical use, protecting farm income, and ensuring stable potato production despite the ongoing evolution of the pathogen.

12. Sustainable management

Sustainable management of late blight (*Phytophthora infestans*) requires an integrated approach combining cultural, biological, and chemical methods to control disease while preserving soil health and minimizing environmental impact. Reducing reliance on synthetic fungicides is crucial due to rising resistance and ecological risks.

Key sustainable practices include:

- Using certified, disease-free seed potatoes and extending crop rotations to avoid solanaceous crops.
- Removing cull piles and volunteer plants, improving soil drainage, and adjusting planting times.
- Employing biological controls like beneficial microbes (*Bacillus subtilis*, *Pseudomonas fluorescens*, *Trichoderma harzianum*) and plant-based extracts.
- Growing resistant potato varieties with stacked resistance genes and utilizing disease forecasting models to optimize fungicide application.

Integrated pest management (IPM) promotes targeted, minimal chemical use with environmentally friendly products to delay resistance. Building resilient farming systems involves crop diversity, improved soil health through cover cropping and composting, and supporting local seed networks.

Collaboration among researchers, extension services, and farmers is essential to translate research into practical, location-specific solutions. Ongoing dialogue and participatory approaches foster sustainable late blight control tailored to real-world conditions.

In summary, sustainable late blight management is a dynamic, adaptive process focused on reducing chemical dependence, applying ecological principles, and strengthening agricultural partnerships to ensure long-term productivity and environmental stewardship.

13. Conclusion

Late blight caused by *Phytophthora infestans* remains a significant threat to global potato production, demanding integrated management beyond pesticides. Success depends on understanding pathogen genetics, accelerating resistant variety development, and combining cultural, chemical, and biological controls. Practical, affordable solutions and farmer support are essential, alongside strong collaboration among researchers, policymakers, and industry. Coordinated efforts will build resilient, sustainable potato farming that safeguards food security worldwide.

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