PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-13
https://doi.org/10.14719/pst.8222

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REVIEW ARTICLE

Sustainable potato production in a changing climate: Challenges and innovations

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OPEN ACCESS

ARTICLE HISTORY
Received: 13 March 2025
Accepted: 08 April 2025
Available online
Version 1.0 : 26 April 2025
Version 2.0 : 30 April 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Priyanka P, Maragatham N, Geethalakshmi V, Muthulakshmi P, Sellamuthu KM, Rajendran L. Sustainable potato production in a changing climate: Challenges and innovations. Plant Science Today. 2025; 12 (2): 1-13. https://doi.org/10.14719/pst.8222

Abstract

Climate change presents a major threat to global agriculture, primarily due to the increasing frequency and intensity of extreme weather events. As the third most important food crop after rice and wheat, potatoes play a crucial role in achieving food security and alleviating malnutrition due to their high productivity and nutritional value. However, potato cultivation remains highly susceptible to environmental stressors, with projections indicating a potential 32 % reduction in tuber yield by 2050. Climate-induced stress influences the virulence and population dynamics of pests and pathogens, heightening the risk of sudden outbreaks due to increased host susceptibility. The development of stress-tolerant potato varieties and the extensive application of fungicides accelerate pathogen resistance evolution, ultimately limiting their long-term efficacy. Additionally, excessive chemical inputs elevate production costs and pose significant environmental risks. To mitigate these challenges, weather-based approaches offer a promising solution by enabling timely management practices through increasing the accuracy of real-time forecasting and dissemination of weather information to farming communities. The integration of proper agronomic practices, suitable breeding techniques and forecasting weather information with crop protection measures can enhance resilience to climate-induced stress. Adopting the Internet of Things (IoT) technologies in precision agriculture can optimize resource use, improve decision-making and contribute to global food security.

Keywords

abiotic stress; climate resilience; integrated management; *Phytophthora infestans*; potato; yield reduction

Introduction

Potato (*Solanum tuberosum* L.) is the third most important food crop globally, following rice and wheat and holds the top rank among non-cereal crops (1). It plays a critical role in global food security, serving as a dietary staple for approximately two-thirds of the world's population. The crop is favored for its high productivity compared to most cereal crops and its exceptional nutritional profile. Potatoes are a rich source of carbohydrates, high-quality protein with essential amino acids like lysine and threonine and an array of vitamins (Vitamin C, B1, B3 and B6) and minerals (potassium, iron and magnesium) (2). With their low-fat content (0.1 %-1.1 %), low calorie density and high dietary fiber, potatoes are often referred to as the "underground apple", further highlighting their significance in addressing global nutrition and food security.

Despite their global importance, potato crops are highly susceptible to the adverse impacts of climate change. Both biotic and abiotic stresses threaten potato production, with potentially severe implications for global food systems. By 2050, it is estimated that overall potato yields may decrease by as much as 32 % due to abiotic stress factors such as rising temperatures, changing precipitation patterns, frost and salinity (3). Among biotic stresses, late blight (LB), caused by *Phytophthora infestans*, is the most widespread and devastating disease affecting potato cultivation globally. In severely affected fields, late blight can result in yield losses of 70-100 % (4).

The well-established "disease triangle" in plant pathology underscores the critical role of weather variables-such as temperature, humidity and rainfall-in the interaction between a susceptible plant host, a virulent pathogen and the environment (5). As an extension of this concept, time has been introduced as the fourth dimension, emphasizing that disease onset and severity are influenced by the duration for which these three factors align (6). These weather variables impact both the growth and development of the host plant and the pathogen. When environmental conditions favor pathogen activity and plant susceptibility, disease outbreaks are most severe. Conversely, deviations from this "disease optimum" can mitigate disease severity, highlighting the crucial influence of weather on the emergence and spread of plant diseases, including late blight.

According to SDG 13 (Climate Action), mitigating the negative impacts of climate change on potato production requires the adoption of sustainable management and adaptation strategies. These include the development of climate-resilient potato cultivars, optimization of irrigation management, application of biotechnological innovations such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology, integration of crop rotation practices, utilization of true potato seeds, adoption of climate-smart agricultural techniques and enhancement of weather-based early warning systems.

This review examines the impact of climate change on potato growth and development, focusing on key abiotic factors such as rising temperatures, drought, waterlogging, chilling and frost. Additionally, it explores economically significant biotic stressors affecting potato yield, particularly emphasizing the impact of *P. infestans*. Furthermore, the review evaluates various adaptation strategies to mitigate these challenges and ensure sustainable potato production, thereby contributing to achieving the Sustainable Development Goals, specifically SDG 1 (No Poverty) and SDG 2 (Zero Hunger).

Impact of abiotic stress on potato cultivation

***High temperature stress**:* Global surface temperatures have risen by approximately 1.09 °C between 2011 and 2020 compared to pre-industrial levels, with projections indicating an increase of around 1.5 °C by 2050 and 2-4 °C by 2100. This rapid warming poses a serious threat to agriculture, particularly to potato cultivation, which thrives under specific climatic conditions. Potatoes are a versatile crop grown in diverse climates, including tropical, subtropical and temperate regions, yet they perform optimally in moderately cool environments. Their cultivation is primarily concentrated in two regions: (i) between 45° N and 57° N, where they grow as a summer crop and (ii) in subtropical lowlands between 23° N and 34° N, where they are cultivated during the winter season (7). Each stage of the potato life cycle depends on specific temperature requirements (Fig. 1) and deviations from these optimal conditions can trigger morphological, physiological and biochemical changes that negatively impact growth, yield and quality.

Rising temperatures alter the morphology of potato plants by reducing leaf area and count, increasing lateral branching, promoting excessive plant height and diminishing tuber size and number. These structural changes disrupt the source-sink relationship, leading to lower tuber yield and quality. Heat stress during the growing season also causes deformities such as bottleneck tubers, chain tuberization, second growth and heat sprouts, further degrading tuber quality (8). Heat stress severely disrupts photosynthesis and carbohydrate metabolism at the physiological and biochemical levels. Elevated temperatures impair photosystem II, reducing photosynthetic efficiency (9, 10). A 5 °C increase above the optimal temperature lowers the photosynthetic rate by approximately 25 %, leading to reduced biomass accumulation and weakened sink activity (11, 12).

Growth stages	Germination	Leaf development	Shoot & Root elongation	Tuber initiation	Tuber setting/ Pre flowering	Tuber bulking/ Flowering	Tuber bulking	Tuber maturity
Duration	0-9	10-19	20-29	40-49	60-69	70-79	80-89	90-99
Optimum temperature	24-26 °C	20-25 °C	28-30 °C	22 °C	15 °C	15-20 °C	15-20 °C	15-20 °C
	←				Leaf photosynthesis: 16-25 °C		→	

Fig. 1. Optimum temperature ranges for potato growth stages.

Carbohydrate metabolism is crucial for energy production, starch storage and mobilization in potatoes. However, high temperatures increase the accumulation of reducing sugars in tubers, compromising their cooking quality (13). The activity of starch synthase declines under heat stress, slowing starch deposition and tuber growth (14). Additionally, elevated temperatures stimulate gibberellin synthesis, further inhibiting starch synthase activity, restricting sucrose partitioning within the tuber and impairing tuber initiation and development (15). Temperature plays a pivotal role in the partitioning of assimilates from source to sink, directly influencing tuberization. Consequently, heat stress significantly hampers overall crop growth and productivity, posing a major challenge to sustainable potato cultivation in a warming climate.

Low temperature stress : Potato cultivars exhibit high sensitivity to frost, with low temperatures significantly restricting their geographical distribution and contributing to substantial yield losses across millions of hectares annually (16). Cold stress, encompassing both chilling (0-12 °C) and freezing (<0 °C) temperatures, represents a major constraint to global potato production (17). Freezing stress during the seedling stage leads to severe growth suppression and yield reduction. Growth inhibition in potato seedlings is observed below 7 °C, with chilling injury becoming apparent at -0.8 °C, frost damage occurring at -2 °C and complete seedling mortality at -3 °C (18).

Plants develop adaptive mechanisms to cold stress, a process referred to as cold hardening. This involves metabolic reprogramming in response to freezing temperatures, leading to alterations in stress hormone levels such as abscisic acid (ABA) (19), proline (20) and malondialdehyde levels (21, 22). However, excessive accumulation of plant growth regulators, particularly ABA and gibberellins, disrupts metabolic homeostasis. While ABA plays a crucial role in cold resistance, its overaccumulation induces excessive stomatal closure, reducing CO_2 uptake, lowering photosynthetic efficiency and ultimately diminishing plant productivity (23). Similarly, gibberellins contribute to cold stress adaptation by enhancing membrane stability and promoting tissue repair; however, their dysregulation under prolonged cold stress can result in abnormal growth patterns, inefficient resource allocation and reduced tuber formation (24). These physiological disturbances further impair intracellular Ca^{2+} homeostasis, promote lipid peroxidation and compromise the plant's ability to recover from stress (25). In addition, the cold conditions damage the leaf tissues and creates oxidative stress due to increase in the activities of superoxide dismutase (SOD) and peroxidase (POD) enzymes (26).

During tuberization, a temperature of 4 °C leads to a rapid decline in tuber respiration, significantly slowing down developmental processes. When temperatures drop below -2 ° C, tuber formation ceases entirely (27, 28). In addition, exposure to chilling temperatures of 10°C markedly inhibits plant height, reduces chlorophyll content and lowers photosynthetic efficiency. As climate change intensifies, extreme temperature fluctuations are expected to increase the frequency and severity of frost events, posing a substantial threat to potato cultivation. While the accumulation of osmotic regulators under cold stress initially provides protection, prolonged exposure may lead to metabolic imbalances, excessive stomatal closure and prolonged suppression of physiological processes, which in turn, could contribute to long -term yield decline in potato.

Water deficit stress: Climate change has significantly altered global precipitation patterns over the past two decades, increasing the frequency of extreme weather events such as flooding and drought. These changes have critical implications for water availability and quality, primarily due to reduced snowpack accumulation and heightened saltwater intrusion in coastal regions. According to the United Nations Convention to Combat Desertification, the frequency of droughts has risen by 29 %, severely affecting numerous countries across Africa and Europe. In Europe alone, an average of 15 % of the land area experiences drought annually (29).

Potato is recognized for its high water-use efficiency; however, its shallow root system restricts its ability to access water from deeper soil layers, making it highly susceptible to drought stress (30, 31). Studies indicate that potato requires substantial irrigation, particularly from flowering to harvest, with water demands reaching approximately 10 mm every 24-36 hr. This results in a total irrigation requirement of up to 610 mm during the growing season (32). Future climate projections indicate an increasing water demand for potato cultivation, particularly under climate change scenarios in Egypt. Under the Representative Concentration Pathway (RCP) 4.5 emission scenario, water requirements are projected to increase by 5 %, 8.2 % and 10.3 % for the near, mid and long-term periods, respectively. Under the high-emission RCP 8.5 scenario, the projected increases are more pronounced, reaching 5.5 %, 11.4 % and 18.6 % over the same timeframes (33). These findings underscore the growing challenge of sustaining potato production under future climate conditions, necessitating the development of adaptive water management strategies.

Among the various growth stages of potato, the plant emergence and tuber bulking phases are particularly vulnerable to water stress. Drought conditions during these critical stages severely hinder leaf development and significantly impair tuber yield. Studies have shown that under water-deficit conditions, the relative water content of potato cultivars declines by 25-35 %, leading to yield reductions ranging from 47 % to 83 %, depending on the cultivar (34). The duration of water deficit plays a major role in determining tuber yield. For each day of prolonged water deficit for 25 days, yield losses of 3.1 % and 3.4 % have been observed during the vegetative growth and tuberization stages, respectively. This highlights the critical need for maintaining adequate soil moisture, particularly during these sensitive growth phases (35). Additionally, the physiological impact of drought is evident in its effects on photosynthetic efficiency. Drought stress leads to a 45-65% reduction in the electron transport rate (34), thereby diminishing the operational efficiency of photosystem II (PSII) (36). This decline in photosynthetic activity further exacerbates the negative impact on plant growth and productivity.

The increasing frequency and severity of droughts, driven by climate change, pose a significant threat to potato cultivation, particularly in regions with high water demand. The combination of high irrigation requirements, physiological sensitivity to drought and projected increases in future water demand highlights the urgent need for adaptive strategies. These may include breeding drought-resistant potato cultivars, improving water-use efficiency through precision irrigation techniques and implementing soil moisture conservation practices. Addressing these challenges is crucial to ensuring sustainable potato production under future climatic conditions.

Waterlogging stress: Extreme rainfall and flooding present significant challenges to potato production worldwide. More than 10 % of global agricultural land is at risk of excessive rainfall, leading to substantial yield reductions (37). On a global scale, floods were the cause of almost two-thirds of all damage and loss to crops in the period between 2006 and 2016, with a value of billions of dollars (38). Potato crops are particularly vulnerable to waterlogging, which alters soil properties, reduces oxygen availability and disrupts physiological processes such as photosynthesis and respiration (39).

Potatoes have high water requirements but do not tolerate excess moisture (40, 41). Flooding affects plant survival, tuber formation and overall tuber quality. Oxygen deprivation in flooded soils leads to blackheart, a condition where internal tissue decays, forming a black necrotic area in the tuber (42). Additionally, excessive soil moisture increases the risk of bacterial soft rot and lenticel openings, further compromising tuber quality and storability (43).

Experimental data highlight the severe impact of flooding on potato yield. Two days of flooding during the intensive growth phase reduce tuber numbers by 39 %, tuber weight by 41 %, total yield by 64 % and marketable tuber yield by 71 %. Extended flooding of eight days results in nearly complete yield loss (44). At the flowering stage, two days of flooding reduce tuber number by 35 %, tuber mass by 38 % and total yield by 59 %. Longer submergence results in total crop failure (45).

Excess water induced hypoxia triggers physiological responses, including increased levels of ethylene (ET), reactive oxygen species (ROS) and nitric oxide (NO), leading to oxidative stress and plant deterioration (46). Excess moisture also weakens seed tubers and impairs canopy development, reducing overall plant resilience (47).

Recent extreme rainfall events have significantly impacted potato production. In 2023, Europe experienced increased precipitation, leading to substantial crop failures (48). Hundreds of tons of potatoes failed to reach the market in a region where annual per capita consumption is approximately 90 kg. These challenges underscore the need for improved water management strategies and flood mitigation measures to protect potato production from climate variability.

Projection on potato tuber yield for future climate scenario

Studying the impact of climate change on crop production is essential for ensuring global food security. The Intergovernmental Panel on Climate Change (IPCC) provides future climate scenarios in its reports, detailing projected greenhouse gas concentrations, radiative forcing values, their associated impacts and mitigation and adaptation strategies. To assess the potential effects of climate change on crop productivity, researchers simulate crop yields under these future climate scenarios. These simulations improve our understanding of climate-induced yield changes and contribute to the development of advanced technologies and adaptive management strategies to enhance crop resilience (49). Crop yield simulations are conducted using both statistical methods, such as regression analyses and process-based crop models. Process-based models use mathematical equations programmed in computer languages to simulate crop growth and development by integrating environmental data, including weather conditions, soil properties and agronomic practices (50, 51). Table 1 provides critical insights into potential productivity changes in potatoes under future climate conditions.

The Decision Support System for Agrotechnology Transfer - SUBSTOR model projects temperature increases (maximum temperature: +1.2 to +5.6 °C) and a rise in carbon dioxide levels (+2.4 % to +140.9 %), resulting in potato yield changes ranging from -7.2% to +60% in Prince Edward Island, Canada. The InfoCrop model forecasts a maximum temperature rise of +0.2 to +0.6 °C per decade, leading to an 11 % yield decline by 2050 in West Bengal, India. The Light Interception and Utilization model projects an average temperature increase of +2.1 to +3.2 °C, resulting in a significant global potato yield loss of -18 % to -32 % by 2050. The Statistical Regression model indicates an average temperature increase of +1K to +3.3K, with yield reductions ranging from -2.4 % to -65 % in Northeast Lower Saxony, Germany. These projections highlight the substantial impact of climate change on potato productivity, with the most severe declines expected in Germany, India and global estimates by 2050.

Impact of biotic stress on potato cultivation

The potato crop faces significant challenges from biotic constraints, including various insect pests and diseases caused by fungi, bacteria and viruses. The potato has become a staple food source globally due to its cultivation across diverse environmental conditions in over 149 countries. Climate change exacerbates these challenges by increasing insect populations and facilitating the evolution of new pathogen strains across wide geographical areas. This underscores the importance of developing effective management strategies to address these emerging threats. The most economically significant diseases affecting potatoes are late blight (*P. infestans*), early blight (*Alternaria* ssp.), potato virus Y, potato leaf roll virus, bacterial wilt or 'brown rot' (*Ralstonia solanacearum*) and blackleg (*Pectobacterium carotovorum*). Another major pest affecting global potato production is potato cyst nematode (PCN, *Globodera* ssp.) (65).

Viral disease - Potato virus Y

Potato plants worldwide are susceptible to approximately 40–50 different viruses, with Potato virus Y (PVY) being among the most significant due to its efficient transmission by 66 species of aphids (66). PVY poses a major threat to seed tuber production, severely reducing both yield and quality, ultimately leading to seed shortages. The increasing incidence and abundance of aphid vectors in a warming climate are expected to exacerbate the spread of PVY (67). Managing PVY is particularly challenging due to its genetic diversity, with many newly emerged strains and recombinants complicating control efforts. The infection not only reduces yield but also affects tuber quality, with every 1 % increase in PVY incidence leading to a yield reduction of 1.6 cwt per acre (68). The economic impact of PVY infection on

Table 1. Projections of potato production for different locations under future climate scenarios

Model	Data Source	Baseline period	Projections	Yield estimation	Location	Reference
DSSAT-SUBSTOR	CMIP6	1995-2014	Tmax: +1.2 to + 5.6°C Tmin: +1.4 to +6.1°C CO2: +2.4 to +140.9% Rain: +3.4 to +12.8%	In 2050s, -7.2 to 18.8% In 2070s, -10.2 to 60%	PEI, Canada	(52)
Infocrop	HadCM3Q	1981-2010	Tmax: +0.2 to +0.6°C decade^{-1} Tmin: +0.2 to +0.5°C decade^{-1}	In 2050, -11%	West Bengal, India	(53)
LINTUL	CGCM1 CSIRO-Mk2 ECHAM4 GFDLRl5 HadCM2	1961-1990	Tavg : +2.1 to +3.2°C	In 2050s, -18 to -32%	Global	(54)
Statistical Regression	9 GCM 11 RCM	1978-2018	Tavg: +1K to 3.3K	In 2035–65, -2.4% ± 2.2% to -8.4% ± 4.6%	Northeast Lower Saxony (NELS), Germany	(55)
DSSAT DNDC STICS	GFDL-ESM4, IPSL-CM6A, MPI-ESM1-2, MRI-ESM2, UKESM1	1991-2020	GDD: +250 to +562	varies	Canada	(56)
DSSAT-SUBSTOR	CMIP 6	1991-2020	Tmax: +1.7 to +4.0°C Tmin: +1.7 to +4.1°C SRAD: +0.2 to +6.0% Rain: +8.4 to 17.5%	Irrigated: +16 to +30% Rainfed: +16 to +33%	Spring potato at Suwon, South Korea	(57)
			Tmax: +1.7 to +4.1°C Tmin: +1.7 to +4.0°C SRAD: +0.5 to +5.6% Rain: +6.6 to 13.5%	Irrigated: +17 to +23% Rainfed: +15 to +22%	Summer potato at Daegwallyeong, South Korea	
DSSAT-SUBSTOR	5GCM	1980–2009	Tavg: +1.6 to +3.8°C Rain: -1 to -3%	Rainy: -23 to 52.7% Dry: -3.1 to -30.6% Winter: +4.8 to +5.7%	Brazil	(58)
DSSAT – SUBSTOR DSSAR – Perturb (to generate future weather data)	GFDL-CM3, GISS-E2, HadGEM2-ES	1989-2018	Tavg: +1.7 to +2.2°C First frost fall: 13 days to 18 days later	In 2050-2079, -13 to -27% With elevated CO-, -5 to +6%	Maine, U.S.A.	(59)
DSSAT-SUBSTOR	HadGEM2-ES IPSL-CM5A-LR GFDL-ESM2M MIROC-ESM-CHEM NorESM1-M ISI-MIP	1979 -2009	-	Varies	Global	(60)
WOFOST	SRES A1FI pathway (AOGCMs)	1971–2000	CO_2: 590PPM	In 2055, Due to temperature -17.9 to -22.0% Due to CO_2 +17.3 to +51.2% Due to temperature & CO_2 -3.3 to -6.5%	Punjab, India	(61)
DSSAT-SUBSTOR	HadCM3 IPCM4	1982–2012	LARS – WG (Long Ashton Research Station-Weather Generator)	HadCM3: -11.21 to -27.53% IPCM4: -12.60 to -30.58%	Isfahan province, Iran	(62)
APSIM-Potato	CMIP5	1981-2010	Tmax: +1.7 to +4.1°C Tmin: +1.6 to +4.9°C Rain: +4.9 to 15.3%	+7.3 to +51.9%	Zhangbei (ZB) - Rainfed China	(63)
			Tmax: +1.4 to + 3.3°C Tmin: +1.7 to +5.2°C Rain: +1.7 to +13.3%	+5.5 to +41.1%	Wuchuan (WC) - Irrigated China	
WOFOST Infocrop	IMD data	1971-2010	Marksim weather generator	2030: -4 to +2.4% 2060: -2.2 to +2.1% 2080: -0.1 to -5.9%	Bihar, India	(64)

potato yield is estimated at approximately 187.2 million EUR annually in European countries. However, this loss is five times lower than that caused by late blight infection, which accounts for an estimated 900 million EUR in annual losses (69).

Bacterial disease - Bacterial wilt

Bacterial wilt, caused by *Ralstonia solanacearum*, is recognized as the second most significant plant pathogenic bacterium globally, following Pseudomonas syringae, according to international phytobacteriologists (70). This pathogen exhibits an extensive geographic distribution and a broad host range, affecting crops such as banana, plantain, cucurbits, eggplant, Eucalyptus, ginger, groundnut, mulberry, tobacco, tomato and various ornamental plants. Infection typically occurs during the warmest period of the day, leading to characteristic symptoms such as brown discoloration of leaves and the exudation of slimy bacterial ooze from infected tubers (71). Once infected, plants die within 3-4 days, significantly disrupting the potato supply chain. The disease is prevalent in wet equatorial, sub-equatorial and certain temperate regions, affecting approximately 3.75 million acres across 80 countries. The estimated global economic impact exceeds $950 million annually (71).

Soil nematode - Potato cyst nematode (PCN)

The potato cyst nematode (PCN) is a significant pest affecting potato production worldwide, caused by two species: the golden cyst nematode (*Globodera rostochiensis*, gPCN) and the pale cyst nematode (*G. pallida*, pPCN). These invasive pests are reported in 74 and 49 countries, respectively and are distributed across all continents except Antarctica (72). PCNs have a wide host range of approximately 170 species within the Solanaceae family, including economically high value crops (73). The disease often remains undetected for over 30 years post-infestation and is extremely difficult to eradicate (74). PCNs exhibit high environmental adaptability, surviving without a host for up to 30 years (75) and tolerating a broad range of temperatures (76). Under severe infestations, PCNs can cause up to 9 % yield loss in potatoes and, in extreme cases, complete crop failure (77). Economic losses due to PCNs have been substantial; in Australia, gPCN was estimated to cause annual losses of AU$ 11.9-27.0 million (78), while in Idaho, USA, pPCN resulted in a US$26 million loss in total agricultural output in 2006 (79).

Fungal disease - Late blight of Potato

Late blight, caused by *Phytophthora infestans* (Mont.) deBary, remains one of the most economically significant diseases affecting solanaceous crops, particularly potatoes and tomatoes. This oomycete pathogen has a remarkable ability to persist under unfavorable environmental conditions, surviving in soil and plant debris during winter and dry seasons. Its capacity for both asexual and sexual reproduction allows it to spread rapidly and generate new, more virulent strains through genetic recombination, thereby increasing its adaptability to diverse environmental conditions and resistance management strategies.

The global impact of *P. infestans* is substantial, with annual economic losses in potato production alone estimated between $3 and $10 billion, including both crop yield reductions and disease management costs (80). The etymology of Phytophthora, meaning "plant destroyer", accurately reflects its aggressive pathogenic nature and its historical role in severe agricultural crises such as the Irish Potato Famine (81).

While its primary hosts are potatoes (*Solanum tuberosum*) and tomatoes (*Solanum lycopersicum)*, *P. infestans* has also been reported to infect other solanaceous crops, including bell peppers (*Capsicum annuum*) and eggplants (*Solanum melongena*). Additionally, certain ornamental plant species, such as petunias (*Petunia* spp.), have been identified as alternative hosts, further expanding the pathogen's epidemiological significance (82, 83).

Given the rapid evolution of *P. infestans* and the increasing challenges posed by climate change, research efforts are focused on developing integrated disease management strategies. These include breeding for late blight-resistant cultivars, improving early detection and monitoring technologies and optimizing fungicide application protocols. Continued advancements in genomic and molecular studies of *P. infestans* are crucial for understanding its pathogenicity and for developing sustainable control measures to mitigate its impact on global food security.

Epidemiology of Phytophthora infestans

Late blight is a potentially devastating disease that can infect potato foliage and tubers at any stage of crop development. Knowing the symptoms and disease cycle of this rapidly destructive disease is necessary to implement management options. The symptoms start as small, water-soaked spots on lower leaves, expanding into dark brown or black greasy lesions with yellow halos. In cool, wet conditions, white mildew -like growth appears on lesions, which dry out and turn tan in warm weather. Stems and petioles also develop similar lesions and severely infected fields emit a distinct odour. In tubers, irregular brown or purplish spots form on the skin, with dry, reddish-brown rot beneath.

Late blight disease in potatoes, caused by *P. infestans*, is influenced by temperature, humidity, moisture and light. The optimum temperature for fungal growth is 16-24 °C, while sporangia production occurs at 19-22 °C. High moisture (>90 %), night temperatures around 10 °C and free water on plant surfaces promote sporangia germination. At low temperatures (4-12 °C), sporangia release zoospores, whereas at higher temperatures (20 -27 °C), direct germination occurs. Daylight inhibits sporulation, restricting it to nighttime. Cloud cover before rainfall and at least 0.1 mm of rainfall enhances sporangia development. The pathogen struggles at temperatures above 25 °C (84), with indirect germination predominant below 20 °C (85).

Several forecasting models have been developed considering the significance of temperature and moisture for late blight development. These include the Dutch Rules (86), Beaumont's Rules (87), Irish Rules (88), Hyre's System (89), Smith System (90), Wallin's System (91), Forsund System (92), Sharma's Model (93) and the Negative Prognosis Model (94). Utilizing these models criteria, various region-specific decision support systems have been developed across different countries, as presented in Table 2. These models play a crucial role in predicting late blight outbreaks, enabling farmers and researchers to make informed disease management and crop protection decisions.

Management techniques of Phytophthora infestans

Table 2. Decision support systems developed for Late blight management in potatoes

Model	*Input variables*	*Country*	*Developer*
BLITECAST	*Daily rainfall, maximum and minimum temperature*	*Eastern United States*	(95)
LATEBLIGHT	*Rainfall, Temperature, RH*	*USA*	(96)
ProPhy	*Temperature, relative humidity, rainfall and leaf wetness*	*Netherlands*	(97)
WISDOM	Daily rainfall, maximum and minimum temperature, hourly temperature and relative humidity.	*Wisconsin, USA*	(98)
PROGEB - PHYTEB	Hourly temperature, relative humidity and rainfall.	*Germany*	(99)
PhytoPRE	Hourly temperature, relative humidity and rainfall.	Switzerland	(100)
NEGFRY	Hourly temperature, relative humidity and rainfall.	*Denmark, Norway and Sweden*	(101)
JHULSACAST	temperature, relative humidity and rainfall on hourly basis.	*India*	(102)
Shtienberg Model	Hourly temperature, relative humidity, surface wetness and rainfall	*New Zealand*	(103)
SIMBLIGHT 1	*temperature, relative humidity, soil moisture*	*Germany*	(104)
EGY-BLIGHTCAST	Hourly temperature, relative humidity, leaf wetness, precipitation, global radiation and wind speed	*Egypt*	(105)
BlightPro	Hourly temperature & RH, 6hr p	*USA*	(106)
INDO-BLIGHTCAST	Temperature; RH Thermal suitability index, humidity suitability index and late blight severity index.	*India*	(107)
BLITE-SVR	13 weather parameters	*Korea*	(108)
BLIGHTSIM	Hourly temperature and RH	*Ecuador*	(109)
Nærstad model	Temperature, Precipitation, Short wave global radiation, Leaf wetness, Relative humidity, Vapour pressure deficit	*Norway*	(110)

To control late blight effectively, integrating cultural practices with chemical management is essential. Early sowing and wider row spacing improve air circulation, reducing humidity and disease severity. Destroying infected seed tubers eliminates the primary source of inoculum, while selecting disease-free seed tubers ensures a healthier crop. Proper hilling and earthing up help prevent tuber exposure, lowering the risk of infection from airborne sporangia. Planting resistant varieties can enhance yields; however, resistance may decline over time due to the emergence of new, virulent *P. infestans* strains. If not managed properly, these strains can spread, making resistance less effective each year. Harvesting 2-3 weeks after dehaulming reduces soil infection risks, further aiding disease control. Fungicide application plays a crucial role, with protectant fungicides needed weekly and systemic fungicides applied every 10 days after infection. However, excessive fungicide use can lead to environmental damage, resistant pathogen strains and harm to beneficial organisms. Scheduling irrigation based on soil moisture and planting at the right time can further enhance disease control while minimizing environmental risks. The potato cultivar 'Payette Russet', released in the United States and Canada, exhibits resistance to both tuber and foliar late blight, along with high resistance to Potato virus Y (111). This cultivar represents an important advancement in breeding efforts aimed at improving disease resistance while maintaining agronomic performance. However, continuous monitoring and breeding interventions are necessary to ensure long-term resistance stability against evolving pathogen populations.

Climate change adaptation strategies for sustainable potato production

Future climate projections indicate an increasing frequency of extreme weather events such as heatwaves, coldwaves, storms and droughts, which significantly impact crop growth and productivity through both biotic and abiotic factors. These climate-driven changes alter host susceptibility, leading to diverse disease outbreaks across different regions. Abiotic stresses, including salinity, drought and high temperatures, negatively affect photosynthetic efficiency, limiting plant growth and making crops more vulnerable to pest infestations and disease invasions. In extreme cases, these stresses can lead to complete crop failure, exacerbating food insecurity, hunger and poverty, particularly for small-scale farmers. Additionally, climate variability influences pest populations and pathogen virulence. Abiotic factors play a crucial role in shaping plant-pathogen interactions, affecting both plant defense mechanisms and pathogen adaptation. Pathogens continuously evolve to overcome host resistance, increasing the risk of infections and disease proliferation. Abiotic stressors also regulate plant immunity, further complicating disease management strategies. Understanding the complex relationship between climatic variables and plant diseases is essential for ensuring sustainable agricultural practices and ecosystem stability. The following adaptive strategies can help mitigate the adverse effects of climate change on potato cultivation, ensuring food security and reducing malnutrition.

Breeding approaches

In the light of significant challenges associated with potato cultivation, plant breeders need to prioritize the development of crop varieties that exhibit resilience to both biotic and abiotic stresses. In India, the Central Potato Research Institute has developed a new variety, Kufri Karan, which is heat-tolerant and resistant to late blight, six potato viruses and moderately resistant to potato cyst nematodes. However, despite its resistance traits, this variety has not provided farmers with an economically viable yield (112). The simultaneous impact of pathogenic infections and climate change poses a formidable constraint on agricultural productivity by exacerbating these stresses (113). Conventional breeding methods are inherently time-consuming, often requiring 10–15 years for field evaluations and phenotypic screening (114). Subsequently, breeders have adopted marker-assisted selection (MAS), a technique that enables the identification of molecular markers linked to desirable traits such as drought tolerance and disease resistance (115, 116). However, the complexity of agronomic practices and the multigenic nature of stress resistance make the rapid development of new cultivars particularly challenging. Indian potato varieties released with tolerance to biotic and abiotic stress (117) in various periods are given in Table 3.

Cultivation approaches

The adverse effects of biotic and abiotic stressors on crops can

Table 3. Potato varieties tolerant to biotic and abiotic stress

Variety	*Year of release*	*Resistance/ Tolerance*
Kufri Sheetman	*1968*	Frost tolerant
Kufri Lauvkar	*1972*	Heat tolerant
Kufri Dewa	*1973*	Frost tolerant
Kufri Badshah	*1979*	Resistant to late blight, early blight and PVX
Kufri Bahar	*1980*	moderately resistant to geminivirus
Kufri Anand	*1999*	Tolerant to frost
Kufri Surya	*2006*	Tolerant to heat
Kufri Girdhari	*2008*	Highly resistant to late blight
Kufri Neelima	*2010*	Resistant to late blight and PCN
Kufri Lima	*2018*	Extreme resistant to PVX and PVY Tolerant to early heat
Kufri Ganga	*2018*	Tolerant to moderate drought
Kufri Karan	*2019*	High resistance to late blight, six potato viruses and potato cyst nematodes
Kufri Fry0M	*2019*	Resistant to late blight and PVY
Kufri Sahyadri	*2019*	High resistance to potato cyst nematodes
Kufri Thar 1, 2 & 3	*2019*	Drought tolerant

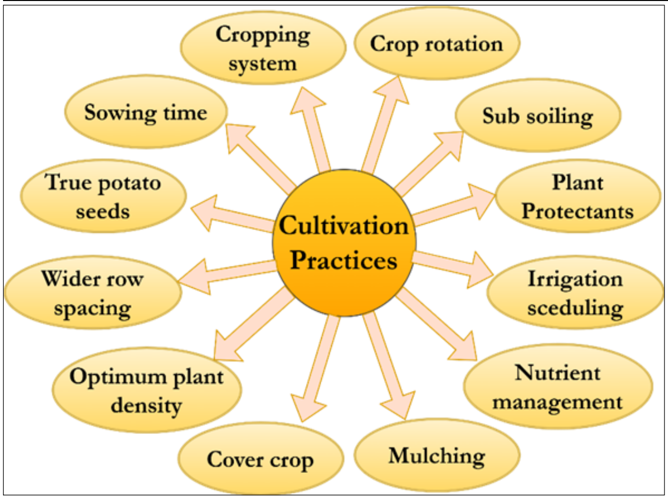

Fig. 2. Cultivation practices to reduce the impact of biotic and abiotic stress.

be mitigated through timely and appropriate management strategies (Fig. 2). One such approach is mulching, which plays a crucial role in reducing soil temperature and conserving soil moisture, particularly under high temperatures and water deficit conditions (118). Similarly, intercropping enhances leaf coverage, thereby lowering soil temperature and improving radiation use efficiency under abiotic stress conditions (119). Potato, being a drought-sensitive crop, requires targeted interventions to minimize the impact of extreme climatic conditions. Several agronomic practices, including mulching (120), irrigation scheduling (121), partial root-zone drying (122), application of rhizobacteria (123) and optimized sowing time, have been shown to enhance water use efficiency, enabling the crop to withstand and escape drought stress. Furthermore, crop diversification emerges as a cost-effective strategy to enhance the resilience of agricultural systems in response to climate change (124). Greater diversity within production systems enhances their adaptability, contributing significantly to food security and nutrition (125, 126). Additionally, diversified cropping systems help mitigate climate change-induced challenges by suppressing pest outbreaks and reducing pathogen transmission risks associated with increased climate variability, thereby stabilizing crop production under climatic stress.

Weather based approaches

Countries worldwide are making substantial investments in meteorological data collection, encompassing the deployment of weather stations, data processing, forecasting and dissemination. The efficacy of these initiatives is maximized when farmers integrate this critical information into their decision-making processes, thereby enhancing crop resilience against unpredictable climatic conditions and improving agricultural productivity (127). This can be facilitated through the dissemination of agrometeorological advisory services from research institutions to farming communities. Such an approach constitutes an effective climate-smart agriculture strategy, enabling the timely adoption of adaptive management practices during crop production.

The development of crop advisories requires the integration of various agronomic and environmental datasets, including regional cropping patterns, predominant crop species, seasonal planting schedules and detailed crop-specific information such as phenological stages, growth duration, varietal preferences and recommended fertilizer applications (128). Additionally, essential data on soil characteristics, pest and disease dynamics-including occurrence stages, symptomatology and management strategies-must be considered. The optimal meteorological conditions required for both crop growth and pest development are also critical parameters. By leveraging medium-range weather forecast data, precise and timely advisories can be generated to support informed decision-making in crop management, thereby enhancing resilience and productivity in agricultural systems.

Utilizing long-range weather forecast data enables the development of region-specific contingency plans, facilitating the selection of suitable crops and optimal management practices well in advance (129). This proactive approach mitigates the negative impact of adverse climatic conditions on crop productivity. Additionally, in the event of imminent extreme weather occurrences, early warning systems can provide timely and reliable adaptation strategies for local farmers, thereby reducing the risk of food insecurity. Moreover, weather-based crop insurance serves as a crucial financial safeguard, helping farmers recover losses caused by extreme weather events such as temperature fluctuations, droughts, floods and humidity variations.

Advancements in genome editing and artificial intelligence for disease management in potatoes

CRISPR/Cas, a novel genome-editing approach, enables precise modifications within the plant genome without introducing foreign genetic material, primarily through site-directed nucleases. This technology holds significant promise for developing transgene-free crop varieties, with biosafety regulations currently under evaluation in multiple countries (130). The incorporation of genes such as StSR4 (131) and Stdmr6-1 (132), knockdown of StNRL1 (133), has been shown to enhance resistance in potato plants against *P. infestans* as well as improve tolerance to abiotic stresses like drought and salinity. Despite its advantages, CRISPR/Cas technology remains constrained by regulatory uncertainties, off-target effects and the time-intensive validation processes required to ensure the stability and effectiveness of edited traits. Additionally, the need for specialized expertise and infrastructure further limits its widespread application, necessitating continued refinement for practical deployment in large-scale breeding programs.

Artificial intelligence (AI) is increasingly being integrated into agriculture for disease detection and forecasting using machine learning and deep learning models. Various deep learning models, including VGG16, VGG19, MobileNet and ResNet50, have been utilized to identify potato diseases. Notably, VGG16 has demonstrated the highest accuracy of 97.89% in classifying late blight and early blight symptoms compared to healthy potato leaves (134). In Cuba, an Android-based mobile application, Potato Crop Diseases (PCD), has been developed using deep learning models to detect disease symptoms in potato plants and suggest targeted management strategies in the field (135).

To enhance the accuracy of disease prediction and forecasting in potatoes, AI-driven research is actively progressing, aiming to mitigate significant crop losses (136). Hyperspectral imaging technology has been explored for early disease detection under greenhouse conditions. However, in field settings, spectral image variations between healthy and infected leaves remain challenging to distinguish clearly (137). Advanced research efforts continue in this area, including the development of machine learning algorithms for the automatic classification of *P. infestans* genotypes into clonal lineages, further strengthening disease surveillance and early warning systems (138).

Conclusion

In conclusion, potatoes, as a staple food crop, are increasingly vulnerable to the impacts of climate change. The effects of rising temperatures, water deficits, flooding and cold waves on crop production and pathogen dynamics have been extensively studied. Given the accelerating pace of climate change and its detrimental effects, immediate and proactive strategies are essential to sustain potato yield rather than relying on time-intensive approaches. A weather-based approach, integrating real-time meteorological data with advisory services, is crucial for timely decision-making. Ensuring that farmers receive weather forecasts and agronomic advisories in advance will enhance their ability to mitigate climate-induced risks. The adoption of IoT (Internet of Things) based tools in precision agriculture can further enhance sustainability by optimizing resource use and improving resilience to climate variability. Additionally, the timely implementation of weather-driven cultivation practices such as optimized planting schedules, targeted fungicidal applications and efficient irrigation management can significantly reduce input costs while improving productivity. A comprehensive, integrated approach that combines advanced breeding techniques, adaptive agronomic practices and decision-support systems will not only enhance potato yield but also contribute to a more sustainable and resilient agricultural system in a changing climate.

Authors' contributions

PP carried out the conceptualization, literature search and data analysis, writing and editing the manuscript. MN participated in the conceptualization and reviewed the manuscript. GV participated in critically revising the manuscript. MP participated in reviewing and editing the manuscript. SKM participated in reviewing and editing the manuscript. RL participated in reviewing and editing the manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Devaux A, Goffart JP, Petsakos A, Kromann P, Gatto M, Okello J, et al. Global food security, contributions from sustainable potato agri-food systems. In: Campos H, Ortiz O, editors. The potato crop: Its agricultural, nutritional and social contribution to humankind. Springer, Cham; 2020. p. 3–35. https://doi.org/10.1007/978-3-030-28683-5_1
2. Bnv P, Gvs S. "Potato"-Powerhouse for many nutrients. Potato Res. 2023;66(3):563–80. https://doi.org/10.1007/s11540-022-09589-2
3. Demirel U. Environmental requirements of potato and abiotic stress factors. In: Potato production worldwide: Academic Press; 2023. p. 71–86. https://doi.org/10.1016/B978-0-12-822925-5.00011-6
4. Islam S, Raihan A, Nahiyan ASM, Siddique MA, Rahman L. Field screening and marker assisted selection of late blight resistant potato lines. Int J Plant Soil Sci. 2018;25:1–12. https://doi.org/10.9734/IJPSS/2018/45301
5. Francl LJ. The disease triangle: a plant pathological paradigm revisited. The Plant Health Instructor. 2001;10. https://doi.org/10.1094/PHI-T-2001-0517-01
6. Pokhrel A. Role of individual components of disease triangle in disease development: a review. J Plant Pathol Microbiol. 2021;12:573.
7. Hijmans RJ. Global distribution of the potato crop. Am J Potato Res. 2001;78:403–12. https://doi.org/10.1007/BF02896371
8. Rykaczewska K. The effect of high temperature occurring in subsequent stages of plant development on potato yield and tuber physiological defects. Am J Potato Res. 2015;92:339–49. https://doi.org/10.1007/s12230-015-9436-x
9. Dahal K, Li X-Q, Tai H, Creelman A, Bizimungu B. Improving potato stress tolerance and tuber yield under a climate change scenario- a current overview. Front Plant Sci. 2019;10:563. https://doi.org/10.3389/fpls.2019.00563
10. Handayani T, Watanabe K. The combination of drought and heat stress has a greater effect on potato plants than single stresses. Plant Soil Environ. 2020;66(4). https://doi.org/10.17221/126/2020-PSE

11. Paul S, Das MK, Baishya P, Ramteke A, Farooq M, Baroowa B, et al. Effect of high temperature on yield associated parameters and vascular bundle development in five potato cultivars. Sci Hortic. 2017;225:134–40. https://doi.org/10.1016/j.scienta.2017.06.061

12. Obiero CO, Milroy SP, Bell RW. Importance of whole plant dry matter dynamics for potato (*Solanum tuberosum* L.) tuber yield response to an episode of high temperature. Environ Exp Bot. 2019;162:560–71. https://doi.org/10.1016/j.envexpbot.2019.04.001

13. Lafta AM, Lorenzen JH. Effect of high temperature on plant growth and carbohydrate metabolism in potato. Plant Physiol. 1995;109(2):637–43. https://doi.org/10.1104/pp.109.2.637

14. Edwards A, Fulton DC, Hylton CM, Jobling SA, Gidley M, Rössner U, et al. A combined reduction in activity of starch synthases II and III of potato has novel effects on the starch of tubers. Plant J. 1999;17(3):251–61. https://doi.org/10.1046/j.1365-313X.1999.00371.x

15. Lovell PH, Booth A. Effects of gibberellic acid on growth, tuber formation and carbohydrate distribution in *Solanum tuberosum*. New Phytol. 1967;66(4):525–37. https://doi.org/10.1111/j.1469-8137.1967.tb05424.x

16. Dong J, Li J, Deng G, Chen C, Jing S, Song B, et al. QTL analysis for low temperature tolerance of wild potato species *Solanum commersonii* in natural field trials. Sci Hortic. 2023;310:111689. https://doi.org/10.1016/j.scienta.2022.111689

17. Beck EH, Heim R, Hansen J. Plant resistance to cold stress: mechanisms and environmental signals triggering frost hardening and dehardening. J Biosci. 2004;29:449–59. https://doi.org/10.1007/BF02712118

18. Fuyi M, Mengyun, L. Potato Cultivation Physiology Beijing: China Agriculture Press; 1995.

19. Huang X, Shi H, Hu Z, Liu A, Amombo E, Chen L, et al. ABA is involved in regulation of cold stress response in bermudagrass. Front Plant Sci. 2017;8:1613. https://doi.org/10.3389/fpls.2017.01613

20. Phukan UJ, Jeena GS, Shukla RK. WRKY transcription factors: molecular regulation and stress responses in plants. Front Plant Sci. 2016;7:760. https://doi.org/10.3389/fpls.2016.00760

21. Yan C, Zhang N, Wang Q, Fu Y, Wang F, Su Y, et al. The effect of low temperature stress on the leaves and microRNA expression of potato seedlings. Front Ecol Evol. 2021;9:727081. https://doi.org/10.3389/fevo.2021.727081

22. Lin Q, Xie Y, Liu W, Zhang J, Cheng S, Xie X, et al. UV-C treatment on physiological response of potato (*Solanum tuberosum* L.) during low temperature storage. J Food Sci Technol. 2017;54:55–61. https://doi.org/10.1007/s13197-016-2433-3

23. Wang X, Guo C, Peng J, Li C, Wan F, Zhang S, et al. ABRE-BINDING FACTORS play a role in the feedback regulation of ABA signaling by mediating rapid ABA induction of ABA co-receptor genes. New Phytol. 2019;221(1):341–55. https://doi.org/10.1111/nph.15345

24. Sun Y, He Y, Irfan AR, Liu X, Yu Q, Zhang Q, et al. Exogenous brassinolide enhances the growth and cold resistance of maize (*Zea mays* L.) seedlings under chilling stress. Agronomy. 2020;10(4):488. https://doi.org/10.3390/agronomy10040488

25. Fu J, Miao Y, Shao L, Hu T, Yang P. De novo transcriptome sequencing and gene expression profiling of *Elymus nutans* under cold stress. BMC Genomics. 2016;17:1–19. https://doi.org/10.1186/s12864-016-3222-0

26. Chen BC, Wu XJ, Guo HC, Xiao JP. Effects of appropriate low-temperature treatment on the yield and quality of pigmented potato *(Solanum tuberosum* L.) tubers. BMC Plant Biol. 2024;24(1):274. https://doi.org/10.1186/s12870-024-04951-7

27. Zommick DH, Knowles LO, Knowles NR. Tuber respiratory profiles during low temperature sweetening (LTS) and reconditioning of LTS-resistant and susceptible potato (*Solanum tuberosum* L.) cultivars. Postharvest Biol Technol. 2014;92:128–38. https://doi.org/10.1016/j.postharvbio.2014.01.020

28. Xia Q. The impact of low-temperature freezing damage on potatoes and defense strategies. Agric Technol. 2021;41(11):3.

29. UNCCD. Drought. UNCCD Publication; 2022.

30. Boguszewska-Mańkowska D, Zarzyńska K, Nosalewicz A. Drought differentially affects root system size and architecture of potato cultivars with differing drought tolerance. Am J Potato Res. 2020;97(1):54–62. https://doi.org/10.1007/s12230-019-09755-2

31. Nasir MW, Toth Z. Effect of drought stress on potato production: A review. Agronomy. 2022;12(3):635. https://doi.org/10.3390/agronomy12030635

32. Byrd SA, Rowland DL, Bennett J, Zotarelli L, Wright D, Alva A, et al. Reductions in a commercial potato irrigation schedule during tuber bulking in Florida: Physiological, yield and quality effects. J Crop Improv. 2014;28(5):660–79. https://doi.org/10.1080/15427528.2014.929059

33. Farag AA, Abdrabbo MA, El-Moula MMHG, Abou HAF, McCarl BA. Water requirements for potato production under climate change. Glob J Adv Res. 2015;2(9):1371–89.

34. Gervais T, Creelman A, Li XQ, Bizimungu B, De Koeyer D, Dahal K. Potato response to drought stress: physiological and growth basis. Front Plant Sci. 2021;12:698060. https://doi.org/10.3389/fpls.2021.698060

35. Li S, Kupriyanovich Y, Wagg C, Zheng F, Hann S. Water deficit duration affects potato plant growth, yield and tuber quality. Agriculture. 2023;13(10):2007. https://doi.org/10.3390/agriculture13102007

36. Baker NR, Harbinson J, Kramer DM. Determining the limitations and regulation of photosynthetic energy transduction in leaves. Plant Cell Environ. 2007;30(9):1107–25. https://doi.org/10.1111/j.1365-3040.2007.01680.x

37. Kaur G, Singh G, Motavalli PP, Nelson KA, Orlowski JM, Golden BR. Impacts and management strategies for crop production in waterlogged or flooded soils: A review. Agron J. 2020;112(3):1475–501. https://doi.org/10.1002/agj2.20093

38. FAO. The impact of disasters and crises on agriculture and food security. In: Rome. FaAO, editor. Rome; 2017.

39. Voesenek L, Bailey-Serres J. Flooding tolerance: O2 sensing and survival strategies. Curr Opin Plant Biol. 2013;16(5):647–53. https://doi.org/10.1016/j.pbi.2013.06.008

40. Liu F, Jensen CR, Shahanzari A, Andersen MN, Jacobsen SE. ABA regulated stomatal control and photosynthetic water use efficiency of potato (*Solanum tuberosum* L.) during progressive soil drying. Plant Sci. 2005;168(3):831–6. https://doi.org/10.1016/j.plantsci.2004.10.016

41. Kifle M, Gebretsadikan TG. Yield and water use efficiency of furrow irrigated potato under regulated deficit irrigation, Atsibi-Wemberta, North Ethiopia. Agric Water Manag. 2016;170:133–9. https://doi.org/10.1016/j.agwat.2016.01.003

42. Terry LA. Blackheart-an emerging problem for the GB potato packing industry. Potato Council Agriculture & Horticulture Development Board. 2015.

43. da Silva WL, Yang KT, Pettis GS, Soares NR, Giorno R, Clark CA. Flooding-associated soft rot of sweetpotato storage roots caused by distinct Clostridium isolates. Plant Dis. 2019;103(12):3050–6. https://doi.org/10.1094/PDIS-03-19-0548-RE

44. Jovović Z, Broćić Z, Velimirović A, Dolijanović Ž, Komnenić A, editors. The influence of flooding on the main parameters of potato productivity. 2021. https://doi.org/10.17660/ActaHortic.2021.1320.17

45. Fukao T, Barrera-Figueroa BE, Juntawong P, Peña-Castro JM. Submergence and waterlogging stress in plants: a review highlighting research opportunities and understudied aspects. Front Plant Sci. 2019;10:340. https://doi.org/10.3389/fpls.2019.00340

46. Sasidharan R, Hartman S, Liu Z, Martopawiro S, Sajeev N, van Veen H, et al. Signal dynamics and interactions during flooding stress. Plant Physiol. 2018;176(2):1106–17. https://doi.org/10.1104/pp.17.01232
47. Zhao F, Zhang Q, Lei J, Wang H, Zhang K, Qi Y. Environmental factors influence the responsiveness of potato tuber yield to growing season precipitation. Crop Environ. 2024;3(2):112–22. https://doi.org/10.1016/j.crope.2024.02.002
48. Edmond C, Geldard R. Extreme weather is driving food prices higher. World Economic Forum. 2024.
49. Timlin D, Paff K, Han E. The role of crop simulation modeling in assessing potential climate change impacts. Agrosyst Geosci Environ. 2024;7(1):e20453. https://doi.org/10.1002/agg2.20453
50. Asseng S, Zhu Y, Basso B, Wilson T, Cammarano D. Simulation modeling: applications in cropping systems. In: Alfen NKV, editors. Encyclopedia of Agriculture and Food Systems. Academic Press; 2014. p. 102–12. https://doi.org/10.1016/B978-0-444-52512-3.00233-3
51. Basso B, Liu L, Ritchie JT. A comprehensive review of the CERES-wheat,-maize and-rice models' performances. Adv Agron. 2016;136:127–32. https://doi.org/10.1016/bs.agron.2015.11.004
52. Adekanmbi T, Wang X, Basheer S, Nawaz RA, Pang T, Hu Y, et al. Assessing future climate change impacts on potato yields-A case study for Prince Edward Island, Canada. Foods. 2023;12(6):1176. https://doi.org/10.3390/foods12061176
53. Banerjee S, Sarmah K, Mukherjee A, Sattar A, Bandopadhyay P. Effect of projected climate scenarios on the yields of potato crop and agronomic adaptation options as evaluated by crop growth model. MAUSAM. 2022;73(1):71–8. https://doi.org/10.54302/mausam.v73i1.5081
54. Hijmans RJ. The effect of climate change on global potato production. Am J Potato Res. 2003;80:271–9. https://doi.org/10.1007/BF02855363
55. Egerer S, Puente AF, Peichl M, Rakovec O, Samaniego L, Schneider UA. Limited potential of irrigation to prevent potato yield losses in Germany under climate change. Agric Syst. 2023;207:103633. https://doi.org/10.1016/j.agsy.2023.103633
56. Jégo G, Crépeau M, Jing Q, Grant B, Smith W, Mesbah M, et al. Potato yield projections under climate change in Canada. Agron J. 2025;117(1):e70017. https://doi.org/10.1002/agj2.70017
57. Kim YU, Webber H. Contrasting responses of spring and summer potato to climate change in South Korea. Potato Res. 2024;67(4):1265–86. https://doi.org/10.1007/s11540-024-09691-7
58. Bender FD, Sentelhas PC. Assessment of regional climate change impacts on Brazilian potato tuber yield. Int J Plant Prod. 2020;14(4):647–61. https://doi.org/10.1007/s42106-020-00111-7
59. Tooley BE, Mallory EB, Porter GA, Hoogenboom G. Predicting the response of a potato-grain production system to climate change for a humid continental climate using DSSAT. Agric For Meteorol. 2021;307:108452. https://doi.org/10.1016/j.agrformet.2021.108452
60. Raymundo R, Asseng S, Robertson R, Petsakos A, Hoogenboom G, Quiroz R, et al. Climate change impact on global potato production. Eur J Agron. 2018;100:87–98. https://doi.org/10.1016/j.eja.2017.11.008
61. Dua VK, Singh BP, Govindakrishnan PM, Kumar S, Lal SS. Impact of climate change on potato productivity in Punjab–a simulation study. Curr Sci. 2013:787–94. https://doi.org/10.1007/978-81-322-0974-4_12
62. Adavi Z, Moradi R, Saeidnejad AH, Tadayon MR, Mansouri H. Assessment of potato response to climate change and adaptation strategies. Sci Hortic. 2018;228:91–102. https://doi.org/10.1016/j.scienta.2017.10.017
63. Tang J, Xiao D, Bai H, Wang B, Liu DL, Feng P, et al. Potential benefits of potato yield at two sites of agro-pastoral ecotone in North China under future climate change. Int J Plant Prod. 2020;14:401–14. https://doi.org/10.1007/s42106-020-00092-7
64. Rana A, Dua VK, Chauhan N, Chaukhande P, Kumari M. Climate change impact on potato (*Solanum tuberosum*) productivity and relative adaptation strategies. J Agrometeorol. 2023;25(3):410–8. https://doi.org/10.54386/jam.v25i3.2181
65. Morris WL, Taylor MA. The solanaceous vegetable crops: Potato, tomato, pepper and eggplant. In: Thomas B, Murray BG, Murphy DJ, editors. Encyclopedia of Applied Plant Sciences (Second Edition). Academic Press; 2017. p. 55–8. https://doi.org/10.1016/B978-0-12-394807-6.00129-5
66. Kreuze JF, Souza-Dias JAC, Jeevalatha A, Figueira AR, Valkonen JPT, Jones RAC. Viral diseases in potato. In: Campos H, Ortiz O, editors. The potato crop: Its agricultural, nutritional and social contribution to humankind. Springer, Cham; 2020. p. 389–430. https://doi.org/10.1007/978-3-030-28683-5_11
67. Torrance L, Talianksy ME. Potato Virus Y emergence and evolution from the Andes of South America to become a major destructive pathogen of potato and other solanaceous crops worldwide. Viruses. 2020;12(12):1430. https://doi.org/10.3390/v12121430
68. Rushton J, Larsen B, Houser A, Pitt WJ, Charkowski AO, Chikh-Ali M, et al. Detection and Characterization of Potato Virus Y (PVY) Strains and Mixed Infections in San Luis Valley, Colorado. PhytoFrontiers™. 2024;4(4):746–59. https://doi.org/10.1094/PHYTOFR-03-24-0028-R
69. Dupuis B, Nkuriyingoma P, Ballmer T. Economic impact of potato virus Y (PVY) in Europe. Potato Res. 2024;67(1):55–72. https://doi.org/10.1007/s11540-023-09623-x
70. Mansfield J, Genin S, Magori S, Citovsky V, Sriariyanum M, Ronald P, et al. Top 10 plant pathogenic bacteria in molecular plant pathology. Mol Plant Pathol. 2012;13(6):614–29. https://doi.org/10.1111/j.1364-3703.2012.00804.x
71. Charkowski A, Sharma K, Parker ML, Secor GA, Elphinstone J. Bacterial diseases of potato. In: Campos H, Ortiz O, editors. The potato crop: Its agricultural, nutritional and social contribution to humankind. Springer, Cham; 2020. p. 351–88. https://doi.org/10.1007/978-3-030-28683-5_10
72. Rowe J. Globodera rostochiensis (yellow potato cyst nematode). CABI Compendium. 2022. https://doi.org/10.1079/CPC.27034.20210102986
73. Sullivan MJ, Inserra RN, Franco J, Moreno-Leheude I, Greco N. Potato cyst nematodes: plant host status and their regulatory impact. Nematropica. 2007:193–202.
74. Trudgill DL, Elliott MJ, Evans K, Phillips MS. The white potato cyst nematode (*Globodera pallida*)–a critical analysis of the threat in Britain. Ann Appl Biol. 2003;143(1):73–80. https://doi.org/10.1111/j.1744-7348.2003.00073.x
75. Perry RN, Moens M. Plant nematology: Cabi; 2006. https://doi.org/10.1079/9781845930561.0000
76. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci. 2007;11(5):1633–44. https://doi.org/10.5194/hess-11-1633-2007
77. Blacket MJ, Agarwal A, Wainer J, Triska MD, Renton M, Edwards J. Molecular assessment of the introduction and spread of potato cyst nematode, *Globodera rostochiensis*, in Victoria, Australia. Phytopathology. 2019;109(4):659–69. https://doi.org/10.1094/PHYTO-06-18-0206-R
78. Hodda M, Cook DC. Economic impact from unrestricted spread of potato cyst nematodes in Australia. Phytopathology. 2009;99(12):1387–93. https://doi.org/10.1094/PHYTO-99-12-1387
79. Koirala S, Watson P, McIntosh CS, Dandurand LM. Economic impact of *Globodera pallida* on the Idaho economy. Am J Potato Res. 2020;97:214–20. https://doi.org/10.1007/s12230-020-09768-2

80. Schiffer-Forsyth K, Frederickson MD, Hedley PE, Cock PJA, Green S. Phytophthora in horticultural nursery green waste-A risk to plant health. Horticulturae. 2023;9(6):616. https://doi.org/10.3390/horticulturae9060616

81. Gallegly ME, Galindo J. Mating types and oospores of *Phytophthora infestans* in nature in Mexico. Phytopathology. 1958;48:274–7.

82. Srisawad N, Petchaboon K, Sraphet S, Tappiban P, Triwitayakorn K. Possible reasons affecting different *Phytophthora infestans* populations in tomato and potato isolates in Thailand. Diversity. 2023;15(11):1121. https://doi.org/10.3390/d15111121

83. Lu J, Liu T, Zhang X, Li J, Wang X, Liang X, et al. Comparison of the distinct, host-specific response of three Solanaceae hosts induced by *Phytophthora infestans*. Int J Mol Sci. 2021;22(20):11000. https://doi.org/10.3390/ijms222011000

84. Jones LR, Giddings NJ, Lutman BF. Investigations of the potato fungus, *Phytophthora infestans*. In: Bulletin VAES, editor. Burlington: University of Vermont; 1912. https://doi.org/10.5962/bhl.title.119162

85. Crosier W. Studies in the biology of *Phytophthora infestans* (Mont.) de Bary. 1934.

86. Van Everdingen E. Het verband tusschen de weersgesteldheid en de aardappelziekte (*Phytophthora infestans*). Tijdschrift Over Plantenziekten. 1926;32:129–39. https://doi.org/10.1007/BF02812973

87. Beaumont A. The dependence on the weather of the dates of outbreak of potato blight epidemics. Mycol Res. 1947;31(1-2):45–53. https://doi.org/10.1016/S0007-1536(47)80005-1

88. Bourke PMA. Potato blight and the weather: a fresh approach. 1953.

89. Hyre RA. Progress in forecasting late blight of Potato and Tomato. 1954.

90. Smith LP. Potato blight forecasting by 90 per cent humidity criteria. Plant Pathol. 1956;5(3). https://doi.org/10.1111/j.1365-3059.1956.tb00093.x

91. Wallin JR. Summary of recent progress in predicting late blight epidemics in United States and Canada. Am Potato J. 1962;39:306–12. https://doi.org/10.1007/BF02862155

92. Førsund E. Late Blight Forecasting in Norway 1957–1980 1. Bull OEPP. 1983;13(2):255–8. https://doi.org/10.1111/j.1365-2338.1983.tb01609.x

93. Sharma KK. Influence of meteorological factors on potato late blight development in North-Western plains of India. J Indian Potato Assoc. 2000;27:1–3.

94. Ullrich J, Schrödter H. Das Problem der Vorhersage des Auftretens der Kartoffelkrautfäule (*Phytophthora infestans*) und die Möglichkeit seiner Lösung durch eine “Negativprognose”. Nachrichtenblatt Deutsch Pflanzenschutzdienst (Braunschweig). 1966;18:33–40.

95. Krause RA, Massie LB, Hyre RA. Blitecast: a computerized forecast of potato late blight. 1975.

96. Bruhn JA, Fry WE. Analysis of potato late blight epidemiology by simulation modeling. Phytopathology. 1981;71(6):612–6. https://doi.org/10.1094/Phyto-71-612

97. Schepers H, editor ProPhy: a computerized expert system for control of late blight in potatoes in the Netherlands. 1995.

98. Stevenson WR, Wyman JA, Kelling KA, Binning LK, Curwen D, Connell TR, et al., editors. Prescriptive crop and pest management software for farming systems involving potatoes. In: Haverkort AJ, MacKerron DKL, editors. Potato Ecology and Modelling of crops under conditions limiting growth. Current Issues in Production Ecology, vol 3. Springer, Dordrecht; 1995. p. 291–303. https://doi.org/10.1007/978-94-011-0051-9_19

99. Gutsche V. PROGEB-a model-aided forecasting service for pest management in cereals and potatoes 1. Bull OEPP. 1993;23(4):577–81. https://doi.org/10.1111/j.1365-2338.1993.tb00552.x

100. Forrer HR, Gujer HU, Fried PM. PhytoPRE-a comprehensive information and decision support system for late blight in potatoes. 1993.

101. Hansen JG, Andersson B, Hermansen A, editors. NEGFRY-A system for scheduling chemical control of late blight in potatoes1995: Boole Press Ltd.

102. Singh BP, Islam AIA, Sharma VC, Shekhawat GS. JHULSACAST: a computerized forecast of potato late blight in western Uttar Pradesh. 2000.

103. Henshall WR, Shtienberg D, Beresford RM. A new potato late blight disease prediction model and its comparison with two previous models. N Z Plant Prot. 2006;59:150–4. https://doi.org/10.30843/nzpp.2006.59.4548

104. Kleinhenz B, Falke K, Kakau J, Rossberg D. SIMBLIGHT1–A new model to predict first occurrence of potato late blight. Bull OEPP. 2007;37(2):339–43. https://doi.org/10.1111/j.1365-2338.2007.01135.x

105. Afifi M, Zayan SAM, Bruce T, Foyer C, Halford N, Keys A, et al. Implementation of Egy-Blight Cast the first computer simulation model for potato late blight in Egypt. Proceedings of Agriculture: Africa’s “Engine for Growth”-Plant Science & Biotechnology Hold the Key at Roth Amsted Research. 2009:12–4.

106. Small IM, Joseph L, Fry WE. Development and implementation of the BlightPro decision support system for potato and tomato late blight management. Comput Electron Agric. 2015;115:57–65. https://doi.org/10.1016/j.compag.2015.05.010

107. Singh BP, Govindakrishnan PM, Ahmad I, Rawat S, Sharma S, Sreekumar J. INDO-BLIGHTCAST–a model for forecasting late blight across agroecologies. Int J Pest Manag. 2016;62(4):360–7. https://doi.org/10.1080/09670874.2016.1210839

108. Gu YH, Yoo SJ, Park CJ, Kim YH, Park SK, Kim JS, et al. BLITE-SVR: New forecasting model for late blight on potato using support-vector regression. Comput Electron Agric. 2016;130:169–76. https://doi.org/10.1016/j.compag.2016.10.005

109. Narouei-Khandan HA, Shakya SK, Garrett KA, Goss EM, Dufault NS, Andrade-Piedra JL, et al. BLIGHTSIM: A new potato late blight model simulating the response of *Phytophthora infestans* to diurnal temperature and humidity fluctuations in relation to climate change. Pathogens. 2020;9(8):659. https://doi.org/10.3390/pathogens9080659

110. Hjelkrem A-GR, Eikemo H, Le VH, Hermansen A, Nærstad R. A process-based model to forecast risk of potato late blight in Norway (The Nærstad model): model development, sensitivity analysis and Bayesian calibration. Ecol Modell. 2021;450:109565. https://doi.org/10.1016/j.ecolmodel.2021.109565

111. Babarinde SO, Al-Mughrabi K, Burlakoti RR, Peters RD, Asiedu SK, Prithiviraj B. Current understanding and future perspectives on pathogen biology and management of potato and tomato late blight (*Phytophthora infestans*) in Canada. Can J Plant Pathol. 2025:1–21. https://doi.org/10.1080/07060661.2024.2448690

112. Subedi S, Ghimire YN, Gautam S, Poudel HK, Shrestha J. Economics of potato (*Solanum tuberosum* L.) production in terai region of Nepal. Arch Agric Environ Sci. 2019;4(1):57–62. https://doi.org/10.26832/24566632.2019.040109

113. Haque MA, Rafii MY, Yusoff MM, Ali NS, Yusuff O, Datta DR, et al. Recent advances in rice varietal development for durable resistance to biotic and abiotic stresses through marker-assisted gene pyramiding. Sustainability. 2021;13(19):10806. https://doi.org/10.3390/su131910806

114. Tiwari JK, Siddappa S, Singh BP, Kaushik SK, Chakrabarti SK, Bhardwaj V, et al. Molecular markers for late blight resistance

breeding of potato: an update. Plant Breed. 2013;132(3):237–45. https://doi.org/10.1111/pbr.12053

115. Caruana BM, Pembleton LW, Constable F, Rodoni B, Slater AT, Cogan NOI. Validation of genotyping by sequencing using transcriptomics for diversity and application of genomic selection in tetraploid potato. Front Plant Sci. 2019;10:670. https://doi.org/10.3389/fpls.2019.00670
116. Slater AT, Schultz L, Lombardi M, Rodoni BC, Bottcher C, Cogan NOI, et al. Screening for resistance to PVY in Australian potato germplasm. Genes. 2020;11(4):429. https://doi.org/10.3390/genes11040429
117. Tiwari JK, Luthra SK, Bhardwaj V, Singh RK, Buckseth T, Kumar R, et al. Indian potato varieties. Indian Hortic. 2021;64(1).
118. Paul S, Farooq M, Bhattacharya SS, Gogoi N. Management strategies for sustainable yield of potato crop under high temperature. Arch Agron Soil Sci. 2017;63(2):276–87. https://doi.org/10.1080/03650340.2016.1204542
119. Nyawade SO, Karanja NN, Gachene CKK, Gitari HI, Schulte-Geldermann E, Parker ML. Intercropping optimizes soil temperature and increases crop water productivity and radiation use efficiency of rainfed potato. Am J Potato Res. 2019;96(5):457–71. https://doi.org/10.1007/s12230-019-09737-4
120. Sadawarti MJ, Singh SP, Kumar V, Lal SS. Effect of mulching and irrigation scheduling on potato cultivar Kufri Chipsona-1 in Central India. Potato J. 2013;40(1).
121. Dash SN, Pushpavathi Y, Behera S. Effect of irrigation and mulching on growth, yield and water use efficiency of potato. Int J Curr Microbiol App Sci. 2018;7(2):2582–7. https://doi.org/10.20546/ijcmas.2018.702.314
122. Xie K, Wang XX, Zhang R, Gong X, Zhang S, Mares V, et al. Partial root-zone drying irrigation and water utilization efficiency by the potato crop in semi-arid regions in China. Sci Hortic. 2012;134:20–5. https://doi.org/10.1016/j.scienta.2011.11.034
123. Liu J, Zhang J, Zhu M, Wan H, Chen Z, Yang N, et al. Effects of plant growth promoting rhizobacteria (PGPR) strain Bacillus licheniformis with biochar amendment on potato growth and water use efficiency under reduced irrigation regime. Agronomy. 2022;12(5):1031. https://doi.org/10.3390/agronomy12051031
124. Mihrete TB, Mihretu FB. Crop Diversification for Ensuring Sustainable Agriculture, Risk Management and Food Security. Glob Chall. 2025:2400267. https://doi.org/10.1002/gch2.202400267
125. Hertel T, Elouafi I, Tanticharoen M, Ewert F. Diversification for enhanced food systems resilience. In: von Braun J, Afsana K, Fresco LO, Hassan MHA, editors. Science and innovations for food systems transformation. Springer, Cham; 2023. p. 207–15. https://doi.org/10.1007/978-3-031-15703-5_11
126. Gora MK, Kumar S, Jat HS, Kakraliya SK, Choudhary M, Dhaka AK, et al. Scalable diversification options delivers sustainable and nutritious food in Indo-Gangetic plains. Sci Rep. 2022;12(1):14371. https://doi.org/10.1038/s41598-022-18156-1
127. Jung J, Maeda M, Chang A, Bhandari M, Ashapure A, Landivar-Bowles J. The potential of remote sensing and artificial intelligence as tools to improve the resilience of agriculture production systems. Curr Opin Biotechnol. 2021;70:15–22. https://doi.org/10.1016/j.copbio.2020.09.003
128. Dheebakaran G, Panneerselvam S, Geethalakshmi V, Kokilavani S. Weather based automated agro advisories: an option to improve sustainability in farming under climate and weather vagaries. In: Venkatramanan V, Shah S, Prasad R, editors. Global Climate Change and Environmental Policy: Agriculture Perspectives. Springer, Singapore; 2020.p. 329–49. https://doi.org/10.1007/978-981-13-9570-3_11
129. Bal SK, Rao KV, Chandran MS, Sasmal S, Singh VK. Weather forecast, agriculture contingency plan and agromet–advisory services for climate resilient agriculture. Indian J Agron. 2021;66:S1–S14.
130. Schmidt C, Schindele P, Puchta H. From gene editing to genome engineering: restructuring plant chromosomes via CRISPR/Cas. aBIOTECH. 2020;1(1):21–31. https://doi.org/10.1007/s42994-019-00002-0
131. Moon KB, Park SJ, Park JS, Lee HJ, Shin SY, Lee SM, et al. Editing of StSR4 by Cas9-RNPs confers resistance to *Phytophthora infestans* in potato. Front Plant Sci. 2022;13:997888. https://doi.org/10.3389/fpls.2022.997888
132. Karlsson M, Kieu NP, Lenman M, Marttila S, Resjö S, Zahid MA, et al. CRISPR/Cas9 genome editing of potato St DMR6-1 results in plants less affected by different stress conditions. Hortic Res. 2024;11(7):uhae130. https://doi.org/10.1093/hr/uhae130
133. Norouzi M, Nazarain-Firouzabadi F, Ismaili A, Ahmadvand R, Poormazaheri H. CRISPR/Cas StNRL1 gene knockout increases resistance to late blight and susceptibility to early blight in potato. Front Plant Sci. 2024;14:1278127. https://doi.org/10.3389/fpls.2023.1278127
134. Chakraborty KK, Mukherjee R, Chakroborty C, Bora K. Automated recognition of optical image based potato leaf blight diseases using deep learning. Physiol Mol Plant Pathol. 2022;117:101781. https://doi.org/10.1016/j.pmpp.2021.101781
135. Pineda MD, Miranda CI, de la Cruz RA, Guerra AL, Cuello PS, Bianchini M. A mobile app for detecting potato crop diseases. J Imaging. 2024;10(2):47. https://doi.org/10.3390/jimaging10020047
136. Fenu G, Malloci FM, editors. Artificial intelligence technique in crop disease forecasting: A case study on potato late blight prediction. Intelligent Decision Technologies: Proceedings of the 12th KES International Conference on Intelligent Decision Technologies (KES-IDT 2020); 2020: Springer. https://doi.org/10.1007/978-981-15-5925-9_7
137. Kool J, Evenhuis A. Early detection of *Phytophthora infestans* in potato plants using hyperspectral imaging, local comparison and a convolutional neural network. Smart Agric Technol. 2023;6:100333. https://doi.org/10.1016/j.atech.2023.100333
138. Patarroyo C, Dupas S, Restrepo S. A machine learning algorithm for the automatic classification of *Phytophthora infestans* genotypes into clonal lineages. Appl Plant Sci. 2024;12(5):e11603. https://doi.org/10.1002/aps3.11603