



REVIEW ARTICLE

# Sustainable potato production in a changing climate: Challenges and innovations

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## 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).

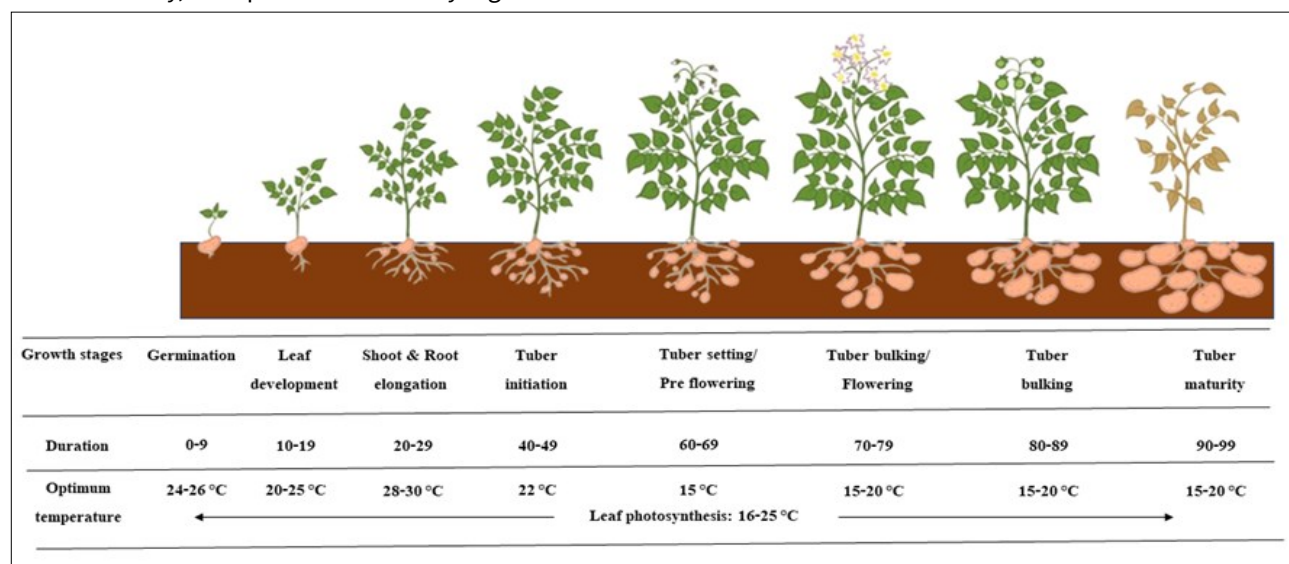


Fig. 1. Optimum temperature ranges for potato growth stages.

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<sub>2</sub> 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<sup>2+</sup> 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* spp.), 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* spp.) (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 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).

**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 CO <sub>2</sub> : +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 <sup>-1</sup> Tmin: +0.2 to +0.5°C decade <sup>-1</sup>	In 2050, -11%	West Bengal, India	(53)
LINTUL	CGCM1 CSIRO-Mk2 ECHAM4 GFDLRI5 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)
DSSAT-SUBSTOR	CMIP 6	1991-2020	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	(57)
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 <sub>2</sub> , -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 <sub>2</sub> : 590PPM	In 2055, Due to temperature -17.9 to -22.0% Due to CO <sub>2</sub> +17.3 to +51.2% Due to temperature & CO <sub>2</sub> -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)
APSIM-Potato	CMIP5	1981-2010	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	(63)
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)



### 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 phytopathologists (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*

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

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

<b>Model</b>	<b>Input variables</b>	<b>Country</b>	<b>Developer</b>
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)
<b>Shtienberg Model</b>	Hourly temperature, relative humidity, surface wetness and rainfall	New Zealand	(103)
SIMBLIGHT 1	temperature, relative humidity, soil moisture	Germany	(104)
EGY-BLIGHCAST	Hourly temperature, relative humidity, leaf wetness, precipitation, global radiation and wind speed	Egypt	(105)
BlightPro	Hourly temperature & RH, 6hr p Temperature; RH	USA	(106)
INDO-BLIGHCAST	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)

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**

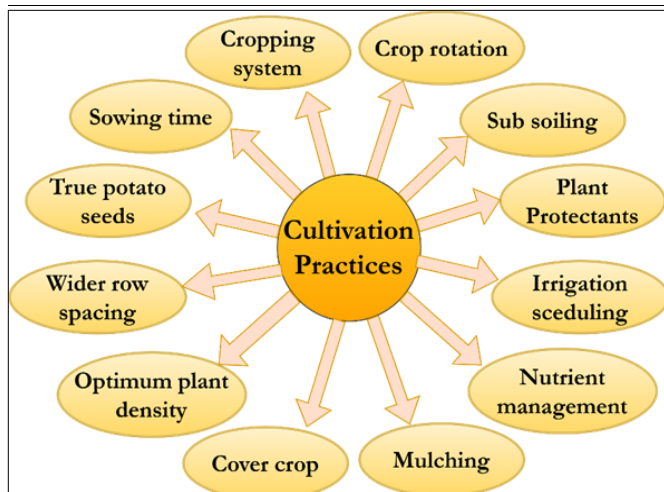
In the light of significant challenges associated with potato cultivation, plant breeders need to prioritize the development of crop varieties that exhibit resilience to both biotic and abiotic stresses. In India, the Central Potato Research Institute has developed a new variety, Kufri Karan, which is 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 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

**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 FryOM	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.

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

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