

Review

## Climate change impacts on tuber crops: Vulnerabilities and adaptation strategies

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### ABSTRACT

Climate change poses significant challenges to root and tuber crops, requiring robust adaptation strategies to mitigate vulnerabilities. This review examines the impacts of climate change on root and tuber crops, including rising temperatures, altered rainfall patterns, extreme weather events, and changes in pest and disease dynamics. These changes significantly affect root and tuber crop production, leading to lower yields, compromised quality, increased susceptibility to pests and diseases, and limited access to water resources. Adaptation strategies encompass various approaches, such as agronomic practices, crop diversification, improved water management, breeding for climate resilience, and agroecological methods. However, addressing knowledge gaps and research needs is crucial for better-understanding climate change impacts and developing effective adaptation strategies for root and tuber crops. Future research should prioritize resilient cultivar identification, enhanced cropping systems, improved pest and disease management, and exploring socio-economic dimensions of adaptation. This review emphasizes the urgent need to address climate change impacts on tropical root and tuber crops. It highlights the critical role of adaptive measures in ensuring long-term sustainability and food security in a changing climate.

**Keywords :** Adaptation strategies, climate change, extreme events, temperature, tuber crops

### INTRODUCTION

Climate change refers to long-term shifts in Earth's climate system due to human activities such as burning fossil fuels and deforestation. These activities release greenhouse gases, trapping heat and gradually raising global temperatures. This has significant implications for agriculture, which heavily relies on weather patterns and water availability. Recognizing the importance of climate change in agriculture is crucial for formulating effective strategies to mitigate its impacts and ensure long-term food security.

Temperature changes have far-reaching consequences for crop growth. Rising temperatures make plants vulnerable to heat stress, negatively affecting their productivity. The Intergovernmental Panel on Climate Change (IPCC) reports highlight the potential geographic shift of crop ranges due to increasing temperatures, impacting their suitability in specific regions (Pachauri *et al.*, 2014). The Earth Observatory (2022) reports that since the inception of the Industrial Revolution, the planet's average temperature has experienced an increase of approximately 1.1°C

(1.9°F), primarily attributed to human activities, particularly the combustion of fossil fuels. Recent years have been marked by record-breaking warmth, with 2022 registering an average global temperature of 14.7°C (58.5°F) (Fig. 1). This warming trend has triggered a cascade of adverse consequences on the planet, including the escalation of sea levels, a surge in the frequency and intensity of extreme weather events, and notable disruptions to both plant and animal ecosystems.

A study by Lobell *et al.* (2011) demonstrated the detrimental effects of elevated temperatures on significant crops such as maize, wheat, and rice, resulting in reduced yields. These findings underscore the vulnerability of tropical root and tuber crops to temperature shifts caused by climate change and emphasize the urgency of implementing adaptation strategies to ensure long-term sustainability.

**Altered precipitation patterns:** They also significantly affect tropical root and tuber crops. Changes in rainfall timing, intensity, and distribution directly influence water availability and soil moisture,



impacting plant growth and productivity. The IPCC reports emphasize the increased likelihood of extreme weather events, including droughts and heavy rainfall, due to climate change. Contingent droughts can lead to water deficit stress in root and tuber crops, affecting tuberization processes and overall yield (Pachauri *et al.*, 2014). Conversely, heavy rainfall events can result in waterlogging, causing oxygen deficiency in the soil and adversely affecting root health and tuber development. Various studies, including Easterling *et al.* (2007), indicate that changes in precipitation patterns have already influenced crop productivity in different regions worldwide. These altered precipitation patterns pose significant challenges to cultivating tropical root and tuber crops and necessitate adaptive strategies, such as improved water management and irrigation techniques, to ensure their resilience and productivity under changing climatic conditions.

**Increased frequency of extreme events:** Climate change is projected to intensify the occurrence and severity of extreme weather events, such as heatwaves, storms, and hurricanes (Hobday *et al.*, 2018). These events have significant implications for tropical root and tuber crops. Heatwaves, for instance, exposed root and tuber crops to prolonged high temperatures, leading to heat stress and reduced photosynthesis. This negatively impacts tuber development and ultimately decreases yields. Intense storms and hurricanes can physically damage crops, uprooting plants and causing lodging, further reducing productivity. A substantial decline in maize and soybean yields in the United States due to extreme heat (Schlenker & Roberts, 2009). Studies highlight the vulnerability of tropical

root and tuber crops to the increasing frequency of extreme events associated with climate change and emphasize the urgent need for adaptive strategies, including improved infrastructure, early warning systems, and crop protection measures, to mitigate the impact of these events and ensure the resilience of root and tuber crops in a changing climate (Tylor *et al.*, 2019).

**Impact on pests and diseases:** Climate change can significantly affect the prevalence, distribution, and dynamics of pests and diseases that harm crops (Skendžić *et al.*, 2021). Temperature and humidity changes can influence the life cycles, geographic ranges, and population dynamics of various pests and diseases (Skendžić *et al.*, 2021; Shrestha, 2019). Warmer temperatures may facilitate the expansion of pests and diseases into new regions, impacting crop productivity. Altered rainfall patterns and increased moisture can create favorable conditions for specific pests and diseases. Higher humidity, for example, promotes the growth of fungal pathogens responsible for tuber rot and leaf blight. Chakraborty *et al.* (2018) emphasize the potential impact of climate change on crop diseases and stress the need for adaptive management strategies to mitigate risks. Integrated pest management practices, including early detection, cultural practices, and biological control methods, may require adjustments to address the changing dynamics of pests and diseases in the context of climate change.

**Food security and livelihoods:** Climate change poses a significant threat to global food security, particularly in regions reliant on tropical root and tuber crops for sustenance and income (FAO, 2015). The Food and

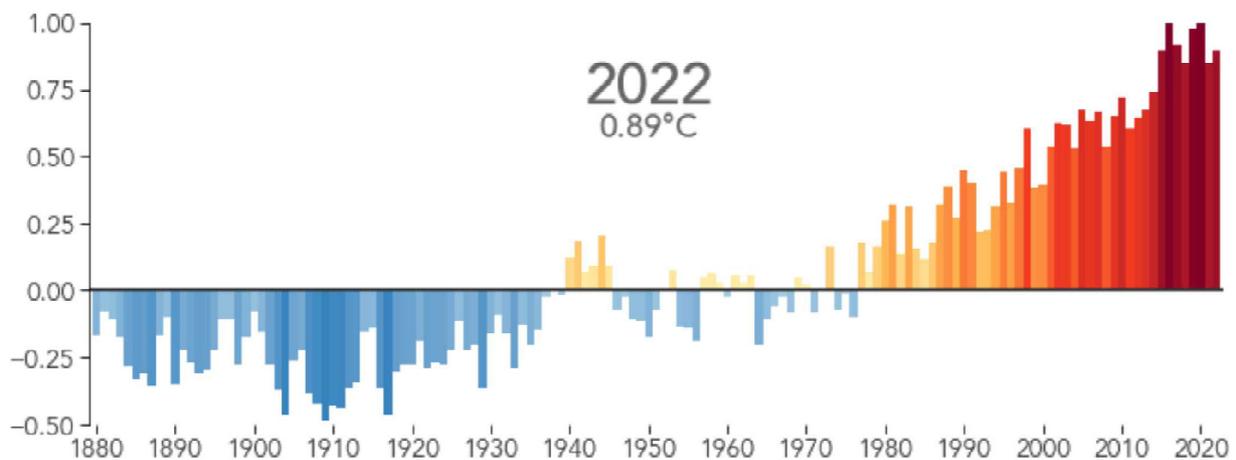


Fig. 1 : Global temperature anomaly compared to the 1950-1980 average (°C)

Source: <https://earthobservatory.nasa.gov/>

Agriculture Organization Report highlights climate change as a significant risk to global food security, exacerbating the challenges of ensuring access to safe and nutritious food for all (FAO, 2015). Smallholder farmers are particularly vulnerable and often engage in subsistence farming with limited resources. Reduced yields and disruptions in agricultural practices can lead to increased food prices, decreased access to nutritious food, and heightened food insecurity. Moreover, smallholder farmers' livelihoods, reliant on root and tuber crops, can be severely affected, undermining economic stability and overall well-being. Addressing climate change's challenges for root, and tuber crops is crucial for food security, poverty alleviation, and sustainable livelihoods in tropical regions. Wheeler and von Braun (2013) provide a comprehensive review of climate change's impacts on global food security, emphasizing the urgent need for effective measures to mitigate these challenges and ensure food availability for vulnerable populations. Parry *et al.* (2004) conducted extensive analysis, considering various emissions and socio-economic scenarios, highlighting the necessity of implementing adaptation strategies for food security in changing climatic conditions. Climate change significantly affects agriculture, including shifting cropping patterns, reduced yields, and increased production costs, necessitating substantial investments in adaptation measures to mitigate negative impacts and ensure long-term food security (Nelson *et al.*, 2009).

Root and tuber crops are essential for food security and the livelihoods of smallholder farmers in tropical regions. Crops like cassava, sweet potato, yam, and taro are well-suited to local climates and thrive in diverse agroecological conditions. They provide nutritional value, resilience, and extended storage capabilities, making them crucial for ensuring food availability, especially in areas with limited access to other food sources. In 2021, significant areas were cultivated for various root and tuber crops. Cassava covered about 29.65 million hectares, 18.13 million hectares of potatoes, 7.41 million hectares of sweet potatoes, taro 1.79 million hectares, yams 8.69 million hectares, and yautia 0.03 million hectares (FAO, 2021). Understanding these trends is vital for sustainable agriculture and global food security. Cassava reached 314.81 million metric tons, potatoes recorded 376.12 million metric tons, sweet potatoes amounted to 88.87 million metric tons, taro

contributed 12.40 million metric tons, yams yielded 75.14 million metric tons, and yautia produced 0.38 million metric tons. These substantial production quantities underline the significance of root crops in meeting global food demands and emphasize the need to manage their cultivation for future food security sustainably.

Research emphasizes the significance of tropical root and tuber crops in achieving food security and supporting smallholder farmers' livelihoods. Studies by Nanbol and Namo (2019) underline how these crops promote dietary diversity, income generation, and employment opportunities for smallholder farmers, particularly in Sub-Saharan Africa and Southeast Asia. The livelihoods of smallholder farmers are heavily dependent on tropical root and root and tuber crops (Owusu *et al.*, 2020; Nedunchezhiyan *et al.*, 2016). The world's top six root and tuber-producing countries, China, India, Nigeria, Indonesia, Brazil, and Thailand, play a critical role in the global food supply. However, climate change poses significant challenges to their root and tuber production. Rising temperatures and unpredictable weather patterns can impact crop growth and yields, decreasing productivity and potential food shortages.

Additionally, extreme weather events such as droughts and floods can disrupt cultivation practices and affect overall food security in these countries, highlighting the urgent need for sustainable agricultural strategies and adaptation measures to safeguard root and tuber production and ensure food resilience in the face of a changing climate. These crops ensure food security for farmers and their households and generate income through local market sales. Moreover, the root and tuber crops value chain provides employment opportunities in processing, transportation, and marketing, contributing to rural economies and poverty reduction. The significant impact of climate change on tuber crops is depicted in Fig. 2.

### **Climate change impacts on tropical root and tuber crops**

#### ***Temperature shifts and their effects***

Rising global mean temperatures have significant implications for the growth and productivity of tropical root and tuber crops. Increased temperatures directly affect physiological processes, altering growth patterns and overall productivity. Research indicates that

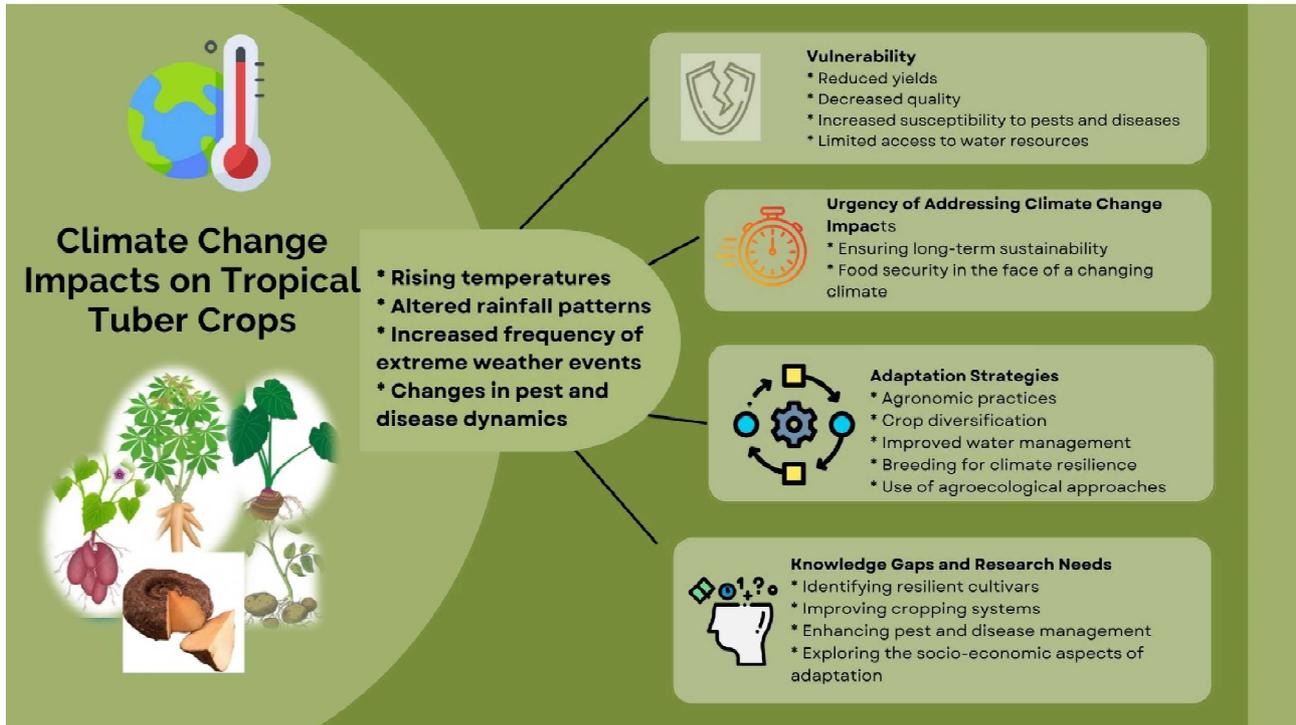


Fig. 2 : Climate change impacts on tuber crops

environmental stresses can reduce the yield of most crops by up to 50% (Reddy *et al.*, 2023; Yadav *et al.*, 2018). High temperatures also compromise the tuber quality of potatoes and sweet potatoes, making them more susceptible to pests and diseases. Additionally, temperature changes can affect the timing of tuber production, posing challenges for crop planning (Reddy *et al.*, 2023).

Elevated temperatures affect root and tuber crops sprouting and establishment. High temperatures hinder seed germination, and delay sprout emergence, affecting overall crop establishment and potentially reducing yields of potatoes. Moreover, rising temperatures expedite developmental stages, resulting in shorter growth cycles and smaller tubers, reducing marketable yield and economic value (Lal *et al.*, 2022). Increased temperatures also impact photosynthesis by inducing physiological stress and reducing carbon dioxide uptake, ultimately affecting tuber growth and yield. Additionally, high temperatures contribute to water deficit stress, exacerbating negative impacts on root and tuber crops, particularly in water-limited regions. Contingent drought stress leads to smaller tubers, lower yields, and potential crop failure. The potato crop is also susceptible to the detrimental

effects of rising temperatures. Elevated temperatures reduce leaf size and quantity, as well as the number of tubers (Lee *et al.*, 2020). The tuber yield of potatoes can decrease by up to 27% under elevated temperatures (Kimball, 2016). These negative consequences have significant implications for food security, potentially driving up food prices and affecting access to an adequate food supply.

Furthermore, the impacts of rising temperatures on crops may lead to shifts in cultivated crop types, impacting the entire food system. Temperature thresholds play a crucial role in determining the yield of root and tuber crops, as each crop has specific temperature requirements for optimal growth. Understanding these thresholds is vital for assessing the potential impacts of temperature fluctuations on root and tuber crop productivity (Balde *et al.*, 2018).

Various temperature stress and optimal temperatures are as follows:

- **Optimal Temperature Range:** Cassava, for example, thrives between 25°C and 32°C, with yields declining outside of this range (Balde *et al.*, 2018). Maintaining temperatures within this optimal range is essential to maximize root and tuber crop yields.

- **High-Temperature Stress:** Elevated temperatures beyond the optimal range can lead to heat stress, reducing yields. Sweet potato is susceptible to high-temperature stress, with yields declining when temperatures exceed 30°C (Kumar *et al.*, 2018). Mitigating the adverse effects of heat stress is crucial for temperature-sensitive crops like sweet potatoes.
- **Cold Temperature Stress:** Cold temperatures below 10°C pose challenges for root and tuber crops. Chilling injury can significantly damage yam plants, resulting in stunted growth and decreased tuber yields (Sanginga *et al.*, 2019). Protecting yam and other root and tuber crops from chilling temperatures is essential for optimal growth and productivity.
- **Freezing Temperatures:** Freezing temperatures significantly threaten root and tuber crops, causing frost damage and plant death. Protecting root and tuber crops from freezing temperatures, such as using coverings or frost-tolerant varieties, minimizes negative impacts and ensures successful tuber production.

Implementing appropriate measures to mitigate the effects of high and low-temperature stress is essential for sustaining root and tuber crop production and safeguarding yields (Kumar *et al.*, 2018; Sanginga *et al.*, 2019). Understanding temperature thresholds and their implications is crucial for optimizing root and tuber crop yields and mitigating the negative impacts of temperature extremes. Farmers and researchers can address the specific temperature requirements and vulnerabilities of root and tuber crops by implementing appropriate management practices and climate adaptation measures. Research has highlighted the critical role of temperature thresholds, especially potato growth, and development, affecting above-ground plant parts and tuber formation. High temperatures can stress crops, leading to a decline in potato and sweet potato yields and potential defects in tuber physiology. To ensure optimal root and tuber crop production and mitigate the adverse effects of high-temperature stress, it is essential to maintain temperatures within the optimal range and implement measures to mitigate extreme temperature events (Hatfield *et al.*, 2011). Heat stress events, intensified by climate change, can disrupt vital physiological processes, reduce yields, and alter

carbohydrate balance and diurnal patterns (Challinor *et al.*, 2005). Understanding the broader impact of high temperatures on crop production is crucial for developing mitigation strategies (Hatfield *et al.*, 2011). Measures such as irrigation, shade structures, and heat-tolerant varieties can help mitigate the adverse effects of high temperatures and enhance root and tuber crop yields (Hatfield *et al.*, 2011).

Heat stress can significantly affect the physiological processes of root and tuber crops, including potatoes, during stages such as flowering and fruit development, leading to defects in tubers. Elevated temperatures also impact potatoes' tuberization, growth, and carbohydrate metabolism (Hastilestari *et al.*, 2018; Lal *et al.*, 2022). Understanding and managing these physiological responses are crucial for sustainable root and tuber crop production (Hastilestari *et al.*, 2018). Implementing strategies such as crop management practices, breeding for heat tolerance, and improving irrigation and water management can help mitigate the adverse effects of high temperatures and ensure food security for root and tuber crops in a changing climate (Xalxo *et al.*, 2020). Farmers and researchers can develop informed strategies to safeguard root and tuber crop production and ensure food security by considering the physiological impacts of heat stress.

#### ***Altered rainfall patterns and their consequences***

Changes in rainfall patterns have significant implications for crop production and food security (Lobell *et al.*, 2008). Adapting to these changes is crucial for sustainable agriculture. Altered rainfall patterns affect water availability, planting schedules, irrigation requirements, and crop yields (FAO, 2015). Variations in rainfall intensity and distribution influence soil moisture, nutrient availability, and the occurrence of waterlogging or drought stress, impacting crop growth (FAO, 2015). Excessive rainfall and waterlogging can reduce crop yields, especially in rainfed systems (Nyakudya and Stroosnijder, 2011). Prioritizing threshold planting dates and avoiding delays mitigate water logging effects (Nyakudya and Stroosnijder, 2011). Temperature stresses and uncertain precipitation patterns also impact crop growth and food security, emphasizing adaptable planting strategies (O'Brien *et al.*, 2021).

Soil management, including supplemental irrigation, optimizes tuber yield and quality, particularly for potatoes (Opena & Porter, 1999). Rainfall patterns

and irrigation practices influence soil moisture and nutrient availability, directly affecting potato tuber yield (Porter *et al.*, 1999). Moderate temperature increases during the tuber bulking stage and varying water availability affect potato yield and quality (Ávila-Valdés *et al.*, 2020). Understanding precipitation, water availability, and crop growth relationships is crucial for water management and sustainable agriculture (Ávila-Valdés *et al.*, 2020). Long-term drought stress harms root and tuber crop yield and quality, and climate change-induced temperature and precipitation fluctuations impact potato tubers (Orsák *et al.*, 2021). Water stress during different growth stages negatively affects potato plant growth, yield, and tuber quality (Wagg *et al.*, 2021). Cassava, a susceptible root and tuber crop, is affected by waterlogged soils and water deficits (Kerddee *et al.*, 2021). Implementing irrigation and water management strategies mitigates the negative impacts of drought and waterlogging on root and tuber crop productivity (Kerddee *et al.*, 2021). Considering these factors in irrigation schedules, water conservation practices, and drought-tolerant variety selection ensures sustainable root and tuber crop production in water-limited environments.

### ***Increased incidence of pests and diseases***

Climate change has significant implications for pests and diseases in root and tuber crops such as cassava (Bellotti *et al.*, 2012). Altered temperatures and rainfall patterns can affect arthropod pests in cassava agroecosystems (Bellotti *et al.*, 2012). Climate change can lead to new pests and diseases in Southeast Asian cassava production (Graziosi *et al.*, 2016). The whitefly species *Bemisia tabaci* is a cassava pest whose prevalence can increase due to climate change (Kriticós *et al.*, 2020). Co-infections of cassava viruses and pest resurgences result in severe symptoms and yield losses (Bisimwa *et al.*, 2019). Investigating climate change's impact on cassava pests is crucial for effective management (Chaya *et al.*, 2021).

Climate change influences pests and diseases in sweet potato and yam crops (Munyuli *et al.*, 2017). Vulnerability to pests like sweet potato butterflies (*Acraea terpsichore*) and African sweet potato weevils (*Cylas brunneus*) is expected to increase under climate change (Okonya & Kroschel, 2013). Models emphasize assessing sweet potato and yam responses to climate change and their interactions with pests

(Raymundo *et al.*, 2014). Estimating the potential distribution of new potato pests, including those affecting sweet potato and yams, is crucial. Insect pest-crop interactions lead to yield losses in sweet potato and yam cultivation (Tonnang *et al.*, 2022). Preparedness and disease-resistant cultivars are essential for managing pests and diseases in sweet potato and yam crops (Smith, 2015). The sweet potato weevil's infestation is influenced by location, altitude, and planting season. Higher temperatures can lead to a higher growth rate and severity of outbreaks (Hue and Low, 2015). In Kerala, India, upland areas experienced more severe tuber damage (4 to 50%) than lowland areas (up to 22%). However, in Kabale district, Uganda, lowland areas (up to 1814 meters above sea level) had more *Cylas* spp. Infestation (77%) compared to higher altitudes (1992–2438 meters above sea level) (23%). Weevil infestation can be reduced by strategic planting and harvesting times and by selecting well-buried root locations. Wet seasons with limited cracks in the soil show lesser damage than dry seasons, which facilitate weevil access to the roots. Understanding and managing pests like sweet potato weevils under climate change is crucial (Hue and Low, 2015). Climate change will expand potato pests' range and increase population densities (Quiroz *et al.*, 2018). Adapting potato crops to higher temperatures, diseases, pests, and water supply conditions is crucial (Haverkort and Verhagen, 2008). Integrated pest management, including cultural, biological, and chemical control methods, effectively minimizes environmental impacts (Singh *et al.*, 2013). Breeding pest-resistant potato varieties reduces reliance on pesticides (Hijmans, 2003). Estimating potential distributions of new potato pests helps anticipate challenges. Adaptation strategies like integrated pest management and breeding for pest-resistant varieties ensure sustainable potato cultivation.

Climate change affects pest life cycles, population dynamics, and disease spread through temperature and humidity changes (Legrève and Duveiller, 2010). Pest populations can be affected by changes in life cycles and temperature requirements (Van der Waals *et al.*, 2013). Climate change impacts the spread and impact of insect pests and livestock diseases. Insects' shorter life cycles under warming conditions affect their abundance (Fand *et al.*, 2018). Changing climate alters insect life cycles, distribution, and fungal infections in crops. It also influences invasive pest species' dynamics and their impact on agriculture

(Dangles *et al.*, 2008). Expanded ranges of crop pests and changes in transmission dynamics challenge food production. The pests and diseases pose significant threats to root and tuber crops, including potatoes and sweet potatoes, and their potential implications are noteworthy. Here are some specific pests and diseases of concern:

- **Late blight** (*Phytophthora infestans*): A devastating disease affecting potatoes with climate change influencing its severity and distribution. The pathogen thrives in cool and moist conditions, making regions with higher humidity and rainfall more susceptible to outbreaks, and climate change can potentially create more favorable environments for its spread.
- **Potato cyst nematodes** (*Globodera* spp.): Microscopic soil-dwelling pests causing root galling and yield reduction in potatoes, influenced by changes in temperature and soil conditions. Climate change affects them by accelerating their life cycle in warmer temperatures, altering soil moisture conditions, weakening plant resistance, and potentially shifting their distribution.
- **Sweet potato weevils** (*Cylas* spp.): Major pests of sweet potatoes, causing damage to foliage and tubers, warmer temperatures, and changes in precipitation patterns can create more favorable environments for the weevils to thrive and reproduce. As these pests expand their range to new areas with suitable climates, sweet potato crops in those regions become more vulnerable to infestations, leading to increased damage to foliage and tubers.
- **Wireworms** (*Agriotes* spp.): Larvae of click beetles that damage potato tubers by tunneling into them, changes in temperature and moisture conditions can impact the behavior and lifecycle of wireworms (*Agriotes* spp.), affecting their activity levels and distribution. Warmer temperatures may accelerate their development and increase feeding rates, while alterations in soil moisture can influence their survival and movement patterns.
- **Cassava brown streak disease** (CBSD): A viral disease affecting cassava plants, causing necrotic lesions on tubers, warmer temperatures can accelerate virus replication and vector activity, promoting disease spread. Changes in rainfall patterns may also enhance the population of vector insects, increasing CBSD transmission to cassava

plants. These climate-related factors contribute to the geographical expansion and severity of CBSD, posing a significant threat to cassava production and food security.

- **Cassava mosaic disease** (CMD): A viral disease-causing leaf mosaics and stunted growth in cassava, warmer temperatures can accelerate whitefly reproduction and virus multiplication, leading to increased disease transmission. Additionally, changes in rainfall patterns may affect whitefly populations, further influencing CMD's distribution and impact on cassava crops.
- **Yam anthracnose** (*Colletotrichum gloeosporioides*): A fungal disease-causing rotting of yam tubers, warmer temperatures, and increased humidity can create more favorable conditions for the fungal pathogen's growth and spread, leading to higher incidences of yam tuber rotting and potential crop losses.
- **Yam nematodes** (*Scutellonema* spp.): Microscopic soil-dwelling pests causing stunting and yield reduction in yams; warmer temperatures can accelerate their life cycle and reproduction, while alterations in soil moisture can affect their movement and survival. These factors contribute to stunting and yield reduction in yam crops, posing challenges for yam growers, especially under the influence of climate change.

These pests and diseases, among others, pose significant threats to root and tuber crops. Climate change can influence their prevalence, distribution, and severity, potentially impacting root and tuber crop production and food security. Effective pest and disease management strategies and adaptation measures are crucial to mitigate the risks associated with these threats and ensure sustainable root and tuber crop production.

### **Vulnerabilities of root and tuber crops to climate change**

Tropical roots and tuber crops, such as cassava, sweet potatoes, yams, elephant foot yam, and taro, are vulnerable to climate change due to their unique characteristics (Yadav *et al.*, 2018). Understanding their adaptation processes and vulnerabilities is crucial for sustainable production and food security (Heider *et al.*, 2021). Researchers have studied the impact of climate change on root and tuber crops in various regions, highlighting the need for resilience-enhancing

strategies (Parker *et al.*, 2019). To address these challenges, focus is placed on seed systems, adaptation strategies, and plant growth-promoting microbes in the rhizosphere (Parker *et al.*, 2019). Like other root and tuber crops, potatoes face climate change's consequences, including temperature rise and increased disease and pest risks (Yadav *et al.*, 2018; Van der Waals *et al.*, 2013). The production of potatoes declined by more than 87% when grown under warmer temperatures in the Peruvian Andes due to the increased incidence of novel pests.

Furthermore, crop quality and value were adversely affected under simulated migration and warming scenarios (Tito and Feeley, 2018), and local farmers may face significant economic losses of up to 2,300 US\$ ha<sup>-1</sup> yr<sup>-1</sup> due to these adverse impacts. Efforts are underway to develop climate-resilient potato varieties and implement integrated pest management practices (Yadav *et al.*, 2018; Hijmans, 2003). The rising concentration of CO<sub>2</sub> contributes to climate change. Research indicates that yam, taro, yam bean, and sweet potato crops have the potential to withstand elevated CO<sub>2</sub> levels, which could be advantageous for cultivating these crops in a changing climate (Ravi *et al.*, 2017; Ravi *et al.*, 2021; Ravi *et al.*, 2022). However, more research is needed to determine the long-term effects of elevated CO<sub>2</sub> on the growth and yield of these crops. It is projected that the potential impacts of climate change, specifically focusing on the mean temperature and total precipitation changes on yam (*Dioscorea* spp.) cultivation, to face growing difficulties in numerous regions across India by 2030 as a consequence of the changing climate (Remesh *et al.*, 2019). Genetic diversity is crucial in selecting stress-tolerant varieties for sweet potatoes and taro (Mukherjee *et al.*, 2015). However, root and tuber crops have limited tolerance to biotic stresses and are susceptible to pests and diseases (George *et al.*, 2017). Specific diseases, such as cassava brown streak disease and cassava mosaic disease, pose a significant threat to cassava (Yadav *et al.*, 2018) due to climate vagaries. To mitigate climate change's adverse effects on root, root, and tuber crops, the focus is placed on enhancing genetic diversity and developing climate-resilient varieties (Mukherjee *et al.*, 2015; George *et al.*, 2017). These efforts aim to cultivate varieties with improved tolerance to climatic stresses, ensuring the sustainability and resilience of root and tuber crop production (Yadav *et al.*, 2018).

## Adaptation strategies for climate resilience

### *Development of climate-resilient varieties*

Developing climate-resilient crop varieties is crucial for adapting to climate change (Acevedo *et al.*, 2020). Small-scale producers in low and middle-income countries have adopted climate-resilient root and tuber crops, enhancing resilience and food security (Acevedo *et al.*, 2020). Countries that consume tubers to a large extent, such as Ethiopia, must address climate-resilient food security (Yimer and Babege, 2018). Breeding programs are pivotal in developing climate-resilient crops with traits like root systems and drought tolerance (Banga and Kang, 2014). A multi-omics approach focusing on the root system has been employed for developing climate-resilient rice (Yoshino *et al.*, 2019) and genomics-assisted breeding aids in understanding stress responsiveness (Kole *et al.*, 2015).

The release of climate-resilient lentils and maize showcases progress in breeding for climate resilience (Gupta *et al.*, 2019; Cairns and Prasanna, 2018). Innovative breeding approaches that integrate traits and address climate challenges are essential for climate-resilient agriculture (Bakala *et al.*, 2020), ensuring sustainable food production under abnormal weather conditions (Maheswari *et al.*, 2015). Breeding techniques are essential for developing climate-resilient tropical root and root and tuber crop varieties. Traditional breeding methods and transgenic approaches offer promise in identifying adaptive traits (Singh and Bainsla, 2014). Genomics-assisted breeding aids in identifying genes associated with adaptive traits, while participatory varietal selection expedites progress (Kole *et al.*, 2015; Jeeva *et al.*, 2020). Innovative technologies such as *in vitro* techniques and artificial pollination support breeding efforts. These approaches, combined with improved breeding methods, aim to ensure food security by developing climate-resilient tropical root and root and tuber crop varieties (Banga and Kang, 2014).

Selecting resilient traits is pivotal in developing crops that withstand drought, heat, and diseases while improving nutrient use efficiency (Monneveux *et al.*, 2013). Drought tolerance encompasses mechanisms like water use efficiency and root traits, with advancements in root phenotyping techniques contributing to breeding strategies

(Wasaya *et al.*, 2018). Promising outcomes are observed by incorporating drought and host plant resistance traits and combining multiple drought-tolerant traits (Low *et al.*, 2020). Genetic tools such as quantitative trait loci mapping and molecular breeding aid in selecting stress-resilient traits (Kumar *et al.*, 2017), enhancing adaptability under challenging conditions. Conventional breeding, molecular breeding, and biotechnological tools are crucial in developing climate-resilient crop varieties. Conventional breeding selects and crosses plants to create new varieties with improved resilience. Molecular breeding utilizes genomic information for precise trait selection (Wasaya *et al.*, 2018), while biotechnological tools introduce specific genes or traits (Kumar *et al.*, 2017). Leveraging research on drought tolerance in cereals can enhance drought tolerance in potatoes (Monneveux *et al.*, 2013). Grafting techniques improve efficiency in drought resistance and water use (Kumar *et al.*, 2017). Together, these approaches develop climate-resilient varieties with traits such as drought tolerance, heat tolerance, disease resistance, and nutrient use efficiency.

### ***Sustainable farming practices***

Sustainable agricultural practices are crucial for enhancing the resilience of tropical root and tuber crops to climate change (Gweyi-Onyango *et al.*, 2021). Investing in sustainable technologies and indigenous knowledge shows promising results in responding to climate change (Olaniyan & Govender, 2023). Ensuring sufficient food production requires actions to mitigate climate change impacts on crops (Yadav *et al.*, 2018). Sustainable production systems and water management practices are necessary for smallholder agriculture and potato production (Yadav *et al.*, 2018; Chartzoulakis & Bertaki, 2015). Stress-tolerant cultivars and cultivation technology change to support sustainable root and tuber crop production (Dahal *et al.*, 2019). Local agricultural production in challenging climates promotes food security and a sustainable food system (Barbeau *et al.*, 2015).

***Soil and water conservation measures:*** Soil and water conservation measures, agroforestry, crop rotation, and integrated pest management contribute to resilient and sustainable farming (Meena *et al.*, 2019; Kumawat *et al.*, 2020; Delgado *et al.*, 2011). Practices like contour farming, mulching, and

conservation tillage prevent soil erosion and enhance soil fertility (Delgado *et al.*, 2011). Cover cropping, agroforestry, and crop residue management conserve water and improve soil moisture (Recha *et al.*, 2014; Kumawat *et al.*, 2020). Agroforestry systems improve soil structure and nutrient cycling (Schoeneberger *et al.*, 2012). These practices support sustainable agriculture, conserve resources, reduce erosion, and manage pests and diseases, ensuring long-term viability and food security in a changing climate.

### ***Agroforestry, crop rotation, multiple cropping systems, and integrated pest management:***

Conservation agriculture and organic farming practices improve soil health and water management and reduce greenhouse gas (GHG) emissions, offering sustainable alternatives (Tahat *et al.*, 2020). Techniques like cover cropping, crop rotation, reduced tillage, and ground cover maintenance enhance soil structure, water infiltration, and erosion control and minimize soil disturbance (Tahat *et al.*, 2020). Organic farming improves water use efficiency, reduces irrigation needs, and minimizes labor inputs (Tahat *et al.*, 2020). Conservation agriculture prevents soil carbon loss, reduces GHG emissions, and maintains ground cover, benefiting carbon sequestration and soil health. Studies highlight conservation agriculture's positive impacts on carbon sequestration, GHG emission reduction, and water use efficiency (Ghosh *et al.*, 2019). Integrating techniques like reduced tillage and cover cropping improves soil health, nutrient cycling, fertility, and water retention (Ghosh *et al.*, 2019). These practices promote sustainable agriculture, benefiting soil fertility, water conservation, and reducing environmental impacts. Conservation agriculture and organic farming provide sustainable alternatives, promoting long-term environmental and agricultural sustainability. They enhance soil health and water management and reduce GHG emissions, contributing to soil fertility, water conservation, and mitigating climate change (Tahat *et al.*, 2020). Implementing these practices improves agricultural productivity while minimizing negative environmental impacts. They are recognized for reducing GHG emissions, increasing carbon sinks, and promoting efficient agricultural resource use (carbon sequestration). Cassava is well adapted to multiple cropping systems, including cereals, legumes, and vegetables. A comprehensive review conducted by Ravi *et al.* (2021) explored the progress made in

multiple-cropping systems centered around cassava cultivation. They found cassava is a promising crop for successful intercropping with the above mentioned crops (Ravi *et al.*, 2021). This symbiotic approach not only aids in enhancing soil fertility but also contributes to higher yields while mitigating the vulnerability to pests and diseases.

### Improved water management

**Precision irrigation techniques:** Efficient water management is vital for sustainable agriculture, particularly in climate change. Precision irrigation techniques like drip and micro-sprinklers optimize water use efficiency (Brar *et al.*, 2022). Drip irrigation delivers water directly to plant roots, minimizing evaporation, while micro-sprinklers provide uniform coverage, reducing wastage, evaporation, or wind drift (Brar *et al.*, 2022). Real-time soil moisture sensors enhance water management by enabling farmers to irrigate only when necessary, preventing over-irrigation.

Water-efficient cropping systems also contribute to sustainable water management. Planting drought-tolerant or low-water requirement crops significantly reduces water consumption (Ghaffar *et al.*, 2022). Crop diversification and multiple cropping optimize water resources by cultivating different crops, enhancing water productivity (Brar *et al.*, 2022). The integration of precision irrigation, rainwater harvesting, and water-efficient cropping systems holds the potential for sustainable water management in the face of climate change (Nikolaou *et al.*, 2020). These practices improve water productivity, minimize wastage, and alleviate pressure on scarce water resources in agriculture. By implementing these strategies, farmers enhance water use efficiency, mitigate water scarcity, and contribute to overall agricultural sustainability. For example, cassava requires approximately 3.0 mm of water daily during summer (Sunitha *et al.*, 2014). Climate change's impact on water availability can be addressed using precision management techniques like micro-irrigation and fertigation to enhance water use efficiency (Pushpalatha *et al.*, 2021). Modeling tools like FAO-AquaCrop help estimate yield and water needs, guiding farmers in making informed decisions for sustainable cassava production and food security amidst changing climate conditions (Sunitha *et al.*, 2023).

**Rainwater harvesting and utilization of alternative water sources:** Rainwater harvesting is valuable for supplementing irrigation and reducing reliance on conventional water sources. Rooftop and surface runoff harvesting collect rainwater for later use in irrigation, increasing water availability for agriculture. Wastewater recycling and drought-tolerant cultivars effectively mitigate climate change impacts on water resources. Wastewater recycling treats and reuses wastewater, reducing pressure on freshwater sources. Drought-tolerant cultivars withstand water scarcity, optimizing water use efficiency (Levy *et al.*, 2013). Implementing wastewater recycling and cultivating drought-tolerant varieties maintain agricultural productivity while minimizing dependence on limited freshwater resources (El-Nashar and Elyamany, 2023). These practices enhance the resilience of agricultural systems to water scarcity and changing climates (Patel *et al.*, 2020; El-Nashar and Elyamany, 2023). Exploring alternative water sources and drought-tolerant cultivars enables farmers to adapt to climate change and ensure water resource sustainability in agriculture.

### Case studies and success stories

Case studies and success stories provide valuable insights into climate change mitigation strategies and their regional applicability. A South African study emphasized neglected and underutilized crops (NUS), such as legumes and root vegetables, for climate adaptation and food security (Mabhaudhi *et al.*, 2017). Underutilized crops (NUS) such as the root vegetables cassava, sweet potato, and yam, and the legumes bambara groundnut, cowpea, faba bean, lentil, and pigeon pea, are a good source of nutrients and can be adapted to a variety of climatic conditions. They have the potential for climate adaptation and food security. These vegetables are all relatively easy to grow and can be adapted to various climatic conditions. They are also a good source of nutrients, which makes them an essential part of a healthy diet. These crops are integrated successfully into agriculture, enhancing sustainability and mitigating climate change. In Kenya, adopting resilient root crops in the agribusiness sector improved food security and livelihoods amid climate variability (Gatonye and Adam, 2022). Root crops as alternatives showcased their potential for climate change adaptation. Biofortification, enhancing crop nutrition, addressed food security challenges amidst climate change (Maqbool *et al.*, 2020). Success stories

highlighted its potential in vulnerable populations. A case study from Mizoram, India, highlighted indigenous technologies and practices for climate change adaptation (Sahoo *et al.*, 2018). Traditional farming practices sustained livelihoods in changing climates. These case studies emphasize the importance of diverse approaches, including NUS crops, resilient root crops, biofortification, and indigenous knowledge, to enhance climate resilience and food security.

### Policy and knowledge gaps

Existing policies and initiatives for tropical root and tuber crop adaptation are vital but require addressing critical gaps. Specific strategies and guidelines tailored to root and tuber crops need to be improved, hindering their resilience (De Costa, 2010). Policies promoting climate-resilient varieties, sustainable farming, and improved water management are needed. Integrating root tuber crop adaptation into broader agricultural policies and research agendas is another crucial gap (Tittonell and Giller, 2013). Mainstreaming adaptation measures ensures support and effective implementation. Comprehensive data and knowledge on root and tuber crops' vulnerability and adaptive capacity need to be improved (UNDP, 2019). Research and monitoring are essential to identify suitable practices. Collaboration among stakeholders is crucial. Engagement, participatory approaches, and knowledge-sharing platforms enable the co-design and implementation of adaptation strategies. Bridging these gaps through specific strategies, policy integration, research, and collaboration is essential for the resilience and productivity of root and tuber crops in a changing climate.

Studying climate change impacts on root and root and tuber crops has revealed crucial knowledge gaps for effective adaptation strategies:

- **Understanding climate effects:** Further research is needed to examine the specific impacts of climate change on root and root tuber crops, including temperature, rainfall, and extreme events, to determine vulnerability and adaptive capacity.
- **Crop modeling:** Crop modeling is essential for developing reliable forecasting systems to predict the effects of climate change on root and tuber crops' productivity. These models provide valuable insights, inform adaptation strategies, and aid decision-making for farmers and agricultural stakeholders. With the arrival of advanced

analytical tools like machine learning, combining climatic, weather, and agricultural data becomes feasible, enabling accurate predictions of annual crop yields at a country level in West African countries (Cedric *et al.*, 2022). Such modeling efforts are crucial for addressing food security challenges and ensuring sustainable agricultural production in the face of climate change.

- **Genetic diversity and breeding:** Assessing root and root and tuber crops' genetic diversity and identifying traits for climate resilience, such as drought and heat tolerance, will guide breeding programs. Nutrient-rich under-utilized crop species (NUCS), including root and tuber crops, are nutrient-rich crops that can improve food security. Omics technologies can help us understand NUCS and improve their stress tolerance. Integrating omics technologies is a promising strategy for improving NUCS (Muthamilarasan *et al.*, 2019)
- Investigating efficient irrigation techniques, water storage, and water-saving practices is crucial for sustainable root and tuber crop cultivation in water-limited environments.
- Promoting agroecology, conservation agriculture, and integrated pest management can enhance root and tuber crop resilience. Research should evaluate their effectiveness in maintaining soil health, managing pests and diseases, and improving productivity.
- Understanding climate change's socio-economic implications on root and tuber crops-dependent communities and identifying supportive policy frameworks are vital. Research should explore barriers, the economic viability of adaptation strategies, and social and gender dimensions.
- Addressing these gaps supports evidence-based strategies and policies for climate-resilient root and root tuber crops, ensuring food security and livelihoods for vulnerable communities.

### CONCLUSION

Climate change challenges tropical root and tuber crops, but effective adaptation strategies exist. Promoting climate-resilient varieties, efficient water management, sustainable farming, and supportive policies are vital. However, research is needed to understand climate impacts, develop crop models, assess genetic diversity, optimize water management,

study sustainable practices, and consider socio-economic aspects. By implementing these strategies and addressing research needs, we can protect root and tuber crops, ensure food security, and support vulnerable communities. Prioritizing these efforts enhances root and tuber crops' resilience and productivity in a changing climate.

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