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Effects of Climate Change on the Spread and Severity of Potato Virus Y: An In-depth Examination

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Authors' contributions

This work was carried out in collaboration between both authors. Author NKA designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors JSP managed the analyses of the study & literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Potatoes are a cornerstone of global agriculture and a fundamental component of diets worldwide, with plant viruses accounting for nearly half of the emerging crop epidemics. Among these, Potato Virus Y (PVY) poses a formidable challenge to potato farming, leading to significant economic repercussions and threats to food security. Understanding the influence of climate on PVY is pivotal in tackling this viral menace. Climatic conditions, including temperature, precipitation, and humidity, play a key role in the behavior of aphids, the primary vectors of PVY, thereby impacting the disease's prevalence in potato fields. With climate change modifying these key weather variables, there's a looming risk of enhanced PVY spread and a shift in its geographical presence. Recognizing and adapting to these climate-induced changes is vital for formulating effective

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strategies and sustainable practices to counter PVY's effects, safeguarding potato crops from this major viral threat. This analysis delves into the complex dynamics between climate change and PVY, focusing on how changes in weather patterns influence the virus's behavior and impact, with the aim of enhancing our preparedness and response to this agricultural challenge.

Keywords: PVY; potato; climate; tomato; aphid; temperature; CO_2; light intensity; wind; rainfall.

1. INTRODUCTION

The potato (*Solanum tuberosum L.*), belonging to the *Solanaceae* family, is a vital crop cultivated across both tropical and subtropical regions worldwide [1]. Ranking as the fourth most important food crop globally after wheat, rice, and maize [2], it is recognized not only as a key agricultural product but also as an industrial crop. Its tubers, primarily used for food and feed, consist of 79% water, 18% starch, 2% protein, and 1% vitamins, along with essential minerals, trace elements, and fats [1]. Potatoes represent a crucial cash crop, particularly in developing countries, where they play a significant role in combatting food insecurity and reducing poverty among smallholder farmers [3]. The top potato producers include nations like China, India, Russia, Ukraine, the USA, Germany, Bangladesh, Poland, France, and Belarus [4]. In Bangladesh, potatoes are a primary food crop, second only to rice and wheat [5], and are key to bolstering food security and offering an alternative to staple foods [6]. The cultivation area extends over 1101914.24 acres [7], underscoring the crop's significant potential in sustainable farming systems aimed at securing food for a global population projected to reach 8.5 billion by 2030 [8]. However, potato yields are threatened by various factors, including diseases caused by fungi, bacteria, viruses, and nematodes, with viruses posing a particularly severe risk to sustainable production. The global economy incurs losses of approximately US$60 billion annually due to crop diseases caused by viruses [9]. Among the numerous viral pathogens affecting potatoes worldwide [10], Potato virus Y (PVY) is identified as the most economically damaging [11]. This virus, which also affects other *Solanaceae* family plants like peppers, tomatoes, and tobacco [12], is ranked as the fifth most significant plant virus globally in terms of scientific and economic impact [13]. PVY not only reduces potato yields but also degrades tuber quality, causing losses ranging from 10% to 90% [14]. Certain strains of PVY, particularly recombinant and necrotic ones, can render tubers unsaleable [15], leading to shortages in certified seeds and financial losses for seed growers. The viability of PVY in tubers means that high virus levels in a producer's field can increase the inoculum level for the next year's seed potato crop, potentially leading to the rejection or downgrading of that year's lots [16]. The extent of these losses varies based on factors such as potato variety, year, weather, and geographic location. Environmental conditions play a pivotal role in disease progression, with each virus-plant interaction uniquely influenced by abiotic or environmental factors [17]. Factors like temperature, precipitation, relative humidity, wind speed, and cloud cover significantly affect PVY severity. Additionally, aphid populations, which are key vectors for PVY transmission, correlate positively with environmental conditions, with early summer typically more conducive to their proliferation than winter [18]. This study aims to explore and elucidate the effects of climatic factors on Potato virus Y, seeking to better understand the dynamics and vulnerabilities of this interaction under varying environmental conditions.

2. HISTORY, TAXONOMY AND CLASSIFICATION

The *Potyvirus* genus, with potato virus Y as its type species, stands as the most substantial group within the *Potyviridae* family, comprising up to 30% of all plant virus species. This family also encompasses five additional genera: *Rymovirus, Macluravirus, Ipomovirus, Bymovirus,* and *Tritimovirus.* Many viruses now recognized under the *Potyviridae umbrella* were initially identified early in the twentieth century, with more discoveries in the 1930s, and a significant increase in identified species from the 1960s onward. Viruses belonging to the *Potyviridae* family are known for their significant impact on plant health, leading to extensive research and literature on the subject. From the mid-1980s, the sequencing of potyviruses' complete genomes opened the door to genetic research, facilitated by the development of full-length, directly infectious cDNA clones or infectious transcripts, a technique also applied to *bymoviruses*. The current criteria for classifying viruses into the *Potyviridae* family focus on characteristics such as the long, flexuous nature of the virus particles, the structure of their genome (positive-sense single-stranded RNA with a 5′ terminal protein and a 3′ poly(A) tail), their gene expression mechanism (through a polyprotein that produces multiple gene products via proteolysis), and specific cytopathological effects, notably the creation of pinwheel- or scroll-like cylindrical cytoplasmic inclusions in the cells of infected plants.

3. SIGNIFICANCE OF POTATO VIRUS Y

Plant viruses pose a significant threat to agricultural productivity worldwide, acting as agents of disease in a variety of crops. The extent of the damage caused by these viruses depends on several factors, including the level of the virus present, characteristics of the host plant (like its genotype and stage of growth), the presence and activity of vectors, and environmental conditions [19]. Potyviruses, for example, are known to cause reductions in tuber yield of up to 80% [10]. Potato virus Y (PVY), given its widespread prevalence and economic ramifications, is considered one of the top 10 plant viruses impacting global agriculture [11]. The susceptibility to PVY varies among potato cultivars; some may be vulnerable and exhibit symptoms, some may be tolerant and show no symptoms while suffering minor yield reductions, and others may be resistant to the virus [20]. The Potato Tuber Necrosis Ringspot Disease (PTNRD), triggered by specific strains of PVY, wreaked havoc on potato yields during the 1980s and 1990s in the Middle East, notably in Lebanon, and in Central European countries like Slovenia, Hungary, and Germany. This disease, affecting a broad spectrum of potato cultivars, resulted in substantial yield losses. The devastation was marked by 18,000 hectares—or 60% of the potato crop—being affected, and more than half of the tubers showing necrosis. The emergence of PVY strains capable of causing tuber necrosis significantly contributed to the severity of the disease, exacerbated by the widespread cultivation of susceptible potato varieties such as Igor, Lola, Monalisa, Rosalie, and Hela in the impacted regions [21]. PVY is notorious for causing considerable damage to potato yields, with losses ranging from 10% to a staggering 100%. The virus also adversely affects tomato yields, leading to reductions of 39% to 75% [22]. It has been estimated that each 1% increase in PVY incidence in seed crops can lead to a yield decrease of approximately 180 kg per hectare, translating to a gross income loss of about $18 per hectare [23]. Virus infection from seed tubers can result in a yield decrease ranging from 10% to 80% under severe conditions [24]. In Brazil's potato industry, PVY is a critical concern, capable of causing losses up to 80% [10]. In Spain, a 30% presence of PVY in seed tubers is projected to result in a 10%–15% yield reduction [20]. However, a Finnish study by [25], found that yield losses from a crop with 10–20% PVY-infected seed tubers were minimal. The significant economic losses and implications for food security underscore the importance of effectively managing and understanding PVY to ensure the sustainability of agricultural practices and crop safety.

4. FIRST REPORTS OF GEOGRAPHICAL DISTRIBUTION OF POTATO VIRUS Y

The occurrence, impact, and spread of virus species across different regions are significantly shaped by factors such as vector presence, climatic conditions, and management practices of host crops or plants [11].

Potato Virus Y (PVY) is widespread, with its presence recorded in numerous areas globally, making it a major concern for a variety of host plants, particularly potatoes, due to their economic importance. The emergence and detection of diverse PVY strains over the years highlight the ongoing risk that PVY represents to solanaceous crops worldwide. Although genome sequencing has become a pivotal method for analyzing the evolutionary relationships of new isolates and determining their genetic grouping, this technique alone does not suffice for assigning a PVY isolate to a specific strain group. Strain classification relies on identifying unique sets of symptoms or reactions that occur when a range of potato varieties, each carrying specific resistance genes, are infected [48].

Table 1. First reports of geographical distribution of PVY

Country	Crop	Reference
Portugal	*Solanum tuberosum*	[26]
France	*Nicotiana mutabilis*	[27]
Switzerland	*Solanum tuberosum*	[28]
China	*K. indica*	[29]
Tajikistan	*Solanum tuberosum*	[30]
Tanzania	*Solanum tuberosum*	[31]
Japan	*Solanum tuberosum*	[32]
Mexico	*Solanum tuberosum*	[33]
Syria	*Solanum tuberosum*	[34]
Jordan	*Solanum tuberosum*	[34]
Pakistan	*Solanum tuberosum*	[35]
Ecuador	*Solanum lycopersicum*	[36]
Kenya	*Solanum lycopersicum*	[37]
Saudi Arabia	*Solanum tuberosum*	[38]
South Africa	*Physalis peruviana L.*	[39]
Zimbabwe	*Capsicum annuum L.*	[40]
Egypt	*Solanum tuberosum*	[41]
Argentina	*Calibrachoa*	[42]
South Korea	*Solanum tuberosum*	[43]
Israel	*Solanum tuberosum*	[44]
India	*Solanum nigrum*	[45]
United States	*Solanum tuberosum*	[46]
Croatia	*Solanum lycopersicum*	[47]

5. GENERAL CHARACTERISTICS OF POTATO VIRUS Y

First identified by Smith in 1931, Potato Virus Y (PVY) is now ranked as the fifth most economically and scientifically significant plant virus [49,13]. As part of the *Potyviridae* family and the *Potyvirus* genus, it belongs to the largest group of plant viruses, which includes 111 recognized and 86 tentative species affecting more than 30 plant families [50] Potyviruses have a genome consisting of a single RNA strand, which is translated into a large polypeptide. This polypeptide is then cleaved by viral proteases through three distinct mechanisms to produce several functional proteins, including the coat protein (CP), which plays a crucial role in forming viral particles. These viruses are known to induce the formation of both cytoplasmic and nuclear inclusions that contain viral protein aggregates within the host cells [51].

PVY itself is a monopartite virus with a genome made up of a single-strand of positive-sense RNA (+ssRNA), measuring roughly 9700 nucleotides long, not including the poly(A) tail [22]. The virus particles are about 730 nanometers in length [52] and 11 nanometers wide [53], with the coat protein making up about 95% of the virion's mass [54]. PVY infections are marked by the presence of non-crystalline amorphous inclusions in the cytoplasm, with distinctive "pinwheel" and "bundle-like" structures [51], and are known to cause mosaic PVY has evolved into multiple strains, categorized into at least 13 distinct subgroups based on biological characteristics or phylogenetic analysis [48,55]. Historically, PVY has been divided into three main strains: PVYO, PVYN, and PVYC, with PVYZ and PVYE sometimes included as additional strains. PVYO is the common strain found worldwide [24], and serotypes are currently distinguished only between PVYO and PVYN strains [16]. Notably, at least nine recombinant genomes have emerged from PVYN and PVYO strains [56], with PVYN:O, PVYN-Wi, and PVYNTN being the most prevalent recombinant strains in potato cultivation [57]. Among these, PVYO has been observed to have the highest virus titer in infected plants, followed by PVYNTN and PVYN:O [15], making it the most common strain across various potato varieties [58]. The biological differences between PVY strains are evident in the phenotypic responses of potato cultivars containing specific hypersensitive resistance genes and the induction of necrotic symptoms in tobacco. Strains PVYC, PVYO, and PVYZ elicit hypersensitivity responses through genes Nc, Ny, or Nz, respectively. Meanwhile, strains like PVYN and PVYE can bypass all three hypersensitivity genes, with PVYN uniquely causing veinal necrosis in tobacco. PVYE is distinguished by its unique phenotypic effects [59,60].

6. SYMPTOMOLOGY OF PVY

Potato Virus Y (PVY) is known for its rapid spread and significant impact on potato plants, inducing marked morphological and physiological alterations. Among these changes are symptoms such as vein necrosis, leaf curling, and the mosaic effect, all of which are associated with changes in the structure and function of chloroplasts within the plant cells [61,62,63]. Certain potato cultivars, like Shepody and Russet Norkotah, may serve as carriers for PVY, facilitating its transmission by aphids, as these cultivars often show no or very mild symptoms despite high levels of viral infection [64,65,66].

Tuberculosis-like symptoms, including discolored bands on the skin and necrotic tissue that extends into the tuber flesh, are indicative of PVY infection [67]. The expression of PVYO symptoms in potatoes varies widely across different cultivars, ranging from mild to severe mosaics, leaf and stem necrosis, premature leaf drop, and in some cases, early plant death [24,66]. Only a select number of isolates are known to cause potato tuber necrotic ringspot disease. PVYO is also responsible for systemic mottling in tobacco [68]. The tobacco veinal necrosis strain PVYN typically causes a range of mosaic symptoms in various potato cultivars, from nearly symptomless to mild [66]. The severity of potato tuber necrosis disease is dependent on the specific cultivar infected, with most PVYNTN isolates and some PVYN:O isolates known to be causative agents [69,70,66]. In general, PVYN causes relatively moderate leaf mottling in most potato cultivars and severe systemic veinal necrosis in tobacco.

Hybrid genotypes, such as PVYN:O and PVYNTN, can develop from mixed infections of common and necrotic strains, leading to the recombination of genetic material [71]. The symptoms exhibited by the PVYC and PVYO strains in tobacco are similar. PVYC, also known as the stipple streak strain, has a distribution that includes Australia, India, and parts of the United Kingdom and continental Europe [24]. In potato cultivars carrying the resistance gene Nc, PVYC infection leads to the appearance of lines in the leaf stipules. Many potato cultivars exhibit a hypersensitive reaction to strains within the PVYC group [72].

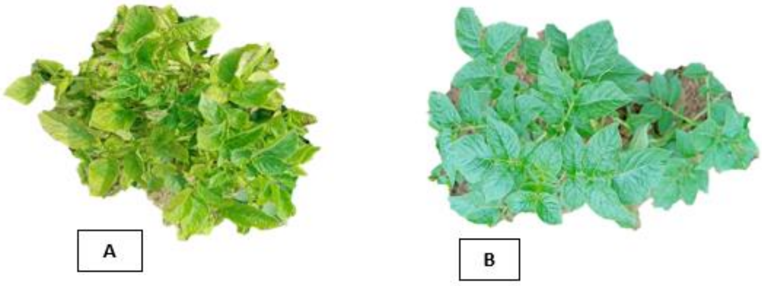

Fig. 1. PVY Infected Potato Plant (A) and Healthy Potato Plant (B), [22]

7. TRANSMISSION OF PVY

Plant viruses, which are obligate parasites, depend on transmission to new hosts for their survival. There are two primary pathways through which plants can become infected by viruses. The first pathway, known as vertical or secondary transmission, involves the spread of the virus from infected seed material, such as a potato tuber, to the emerging plant and subsequently to the daughter tubers. The second mode of transmission, referred to as horizontal transmission, occurs when a plant becomes infected either mechanically or through a vector, typically an insect, which facilitates the spread of the virus to other plants [11]. Potato Virus Y (PVY) can be mechanically transmitted through the use of contaminated tools, direct contact, or rubbing with infected plants. It is also transmitted non-persistently by insect vectors, with the virus being capable of transmission within just a few seconds after being acquired by the vector [73]. Over 65 species of aphids, including both those that colonize potatoes and those that do not, are recognized as vectors capable of transmitting PVY [74], with disease severity reaching up to 73.33% in some cases. All studied potato varieties showed presence of PVY [75]. In peppers, transmission rates of PVY were observed to be between 0.5–3.2 particles per insect per transmission event, a minuscule amount compared to what is found in the sap insects' probe [76,77]. Seasonal patterns of aphid activity also influence PVY transmission. Studies have documented periods of low aphid activity, particularly from July to September, with increased flights noted in June, August, and specific winter months, affecting the likelihood of PVY spread [78,79,80]. The effectiveness of aphid transmission varies by species, with Myzus persicae and Rhopalosiphum padi identified as the most efficient vectors for transmitting PVYNTN isolates, followed by PVYO and PVYN:O isolates [81]. Interestingly, the impact of virus strains on potato tuber mass varies between plants infected mechanically and those infected via aphids, with PVYN:O-infected plants showing higher tuber masses compared to those infected with PVYO or PVYNTN [15].

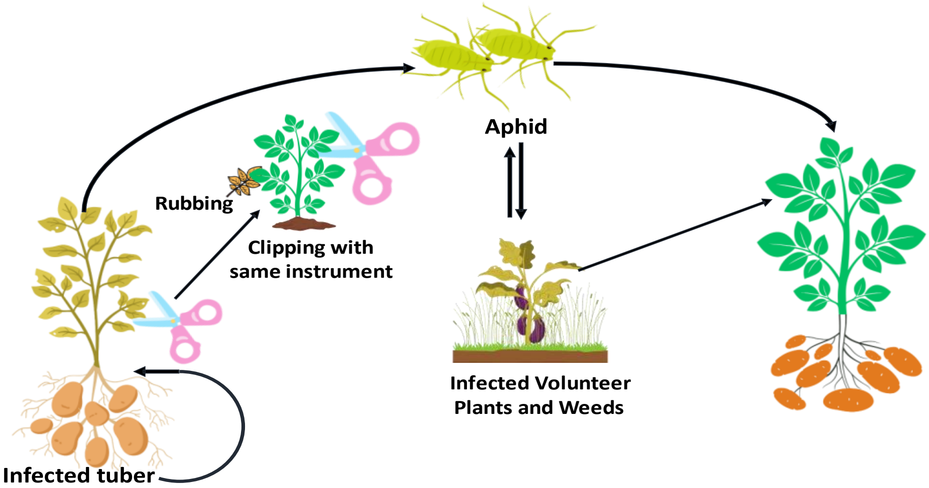

Fig. 2. Transmission Processes of Potato Virus Y, [22]

Landscape characteristics and the presence of natural enemies of vector communities can indirectly influence viral prevalence, with more complex landscapes showing reduced PVY prevalence due to a decrease in species spillover [82,83]. In the plant host, vertical transmission begins with one infected cell, leading to systemic infection throughout the plant as the virus follows the distribution of photo-assimilates, thereby infecting new tubers and growing leaves [84]. Research in Scotland demonstrated that crops grown from seed potatoes from symptomatic plants were four times more likely to present PVY than those from asymptomatic plants [85]. PVY is not known to be transmitted through potato pollen or true seed [86], indicating that effective control measures must target all potential sources of inoculum, including infected plants, weeds, and volunteer plants [87]. The spread of PVY within a crop is influenced by the aphids' ability to transmit the virus and the host plant's susceptibility. Older plants often exhibit greater resistance to infection, possibly due to physical barriers or stronger antiviral responses, compared to younger, more vulnerable plants [88,89].

8. PLANT PHYSIOLOGICAL CHANGES DUE TO PVY

Virus-infected plants exhibit a wide array of symptoms, which may be linked to changes in the activity or levels of plant hormones [90]. Key factors leading to reduced growth rates in virus-infected plants include diminished activity of certain photosynthetic enzymes, increased accumulation of sugars or starch, and compromised photosynthesis due to lower chlorophyll (Chl) content and reduced maximum Chl fluorescence [91,92,93,94]. Research observed that [95] PVY infection significantly lowered the photosynthetic rate (PN) in both transgenic and non-transgenic rooted plants, though it did not affect grafted plants. Factors contributing to the reduced photosynthetic rate included stomatal closure, decreased activity of ribulose-1,5-bisphosphate carboxylase/oxygenase, diminished pigment content in the chlorophyll and xanthophyll cycle, and reduced photosystem II (PSII) activity. Exposure to high light intensity further exacerbated the negative impact on PS II, particularly in rooted plants infected with PVY.

Additionally, the presence of PVY in tobacco plants led to an increase in viral protein levels in non-transgenic plants, whereas transgenic plants showed a decrease. Transgenic plants with elevated endogenous cytokinin (CK) levels exhibited lower viral protein accumulation and fewer PVY symptoms compared to control plants. In the context of PVY infection, transgenic plants accumulated more xanthophyll, whereas healthy plants experienced a decrease in xanthophyll levels under strong light conditions [95]. These observations suggest that the methionine cycle's role in transmethylation is a crucial determinant of a plant's susceptibility or resistance to infection [96]. PVYNTN infection was found to have a minimal impact on intercellular CO_2 concentration but significantly reduced net photosynthetic rate and stomatal conductance. The primary way PVYNTN hinders photosynthesis is by interfering with the enzymatic activities of the Calvin cycle, leading to down-regulation of electron transport [97]. Infected plants also displayed lower chlorophyll levels, alongside changes in chloroplast size and structure [63]. Studies have shown varying responses to PVYNTN infection among different potato cultivars, particularly in the activities of soluble, ionically, and covalently bound peroxidases [98]. Furthermore, interactions between susceptible potato plants and PVYNTN resulted in alterations in cytokinin levels in the inoculated leaves [99].

9. EFFECT OF CLIMATIC FACTORS ON PVY

Environmental factors, including temperature, CO_2 concentration, light intensity, relative humidity, wind speed, and rainfall, profoundly influence the severity of Potato Virus Y (PVY) and the aphid population size. These climate variables are pivotal in hastening the replication of the virus, elevating the likelihood of infection, and facilitating the spread of the virus.

9.1 Effect of Temperature on PVY

The impact of temperature on Potato Virus Y (PVY) dynamics is multifaceted, influenced by direct and indirect effects of climate change, including shifts in environmental conditions and vector behavior. Climate models predict a global average temperature increase of up to 4.6°C by 2100, with more rapid warming in higher latitudes [100]. These changes are anticipated to significantly affect plant virus epidemics, including PVY, by altering host-virus interactions and vector populations [101]. Research by [102] highlights temperature as a crucial environmental factor affecting RNA virus-host interactions differently. For instance, lower temperatures enhanced hypersensitive resistance against PVY in potatoes [103], while at higher temperatures (30°C), PVY was found to suppress antiviral silencing defenses in Nicotiana benthamiana. Systemic PVY infections in potatoes were noted between 16°C to 32°C, with infection times decreasing as temperatures rose [104]. Interestingly, while PVYO infection in Nicotiana benthamiana increased with temperature, it peaked and then declined, with coat protein accumulations being lower at 10°C or 15°C but increasing over time [105]. Symptom expression of PVY in potatoes was more evident at temperatures ranging from 22/17°C to 26/21°C, whereas lower temperatures showed reduced symptoms. This suggests that low temperatures may hinder PVY multiplication and symptom manifestation, a phenomenon observed late in the season with PVY N infections [106]. The Ry chc resistance gene in potatoes showed temperature-dependent reactions; while at 22°C, only minor necrotic spots appeared, at 28°C, clearer necrotic spots emerged, indicating that high temperatures could diminish the resistance provided by the Ry chc gene. However, systemic infection and virus titres were still lower in resistant cultivars at 28°C compared to susceptible ones [107]. High temperatures facilitated systemic PVY infections even in plants exhibiting hypersensitive responses at lower temperatures. Key enzymes in the methionine cycle were downregulated by PVY at higher temperatures, suggesting temperature-sensitive plant-virus interactions [108]. Elevated temperatures also affected salicylic acid (SA) marker expression, with the sensitive cultivar Chicago showing increased susceptibility to PVY, while the resistant cultivar Gala remained less affected [109,4]. Qamar (2016) noted the greatest PVY disease severity at temperatures between 24-28°C maximum and 9-12°C minimum, with a strong correlation between disease progression and temperatures ranging from 15-31°C maximum to 5-13°C minimum. During storage at 22°C, PVY concentrations in dormant tubers decreased [110].

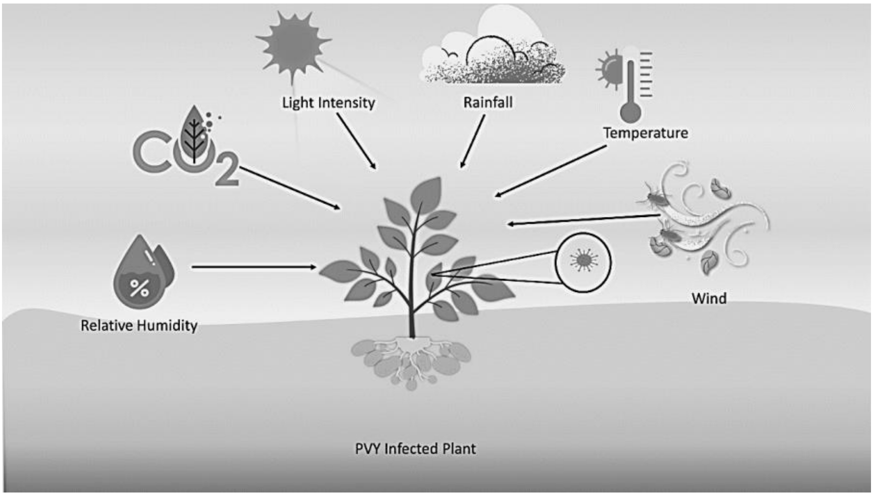

Fig. 3. Effect of Climatic Factors on Potato Virus Y, [22]

Temperature increases may also influence PVY spread by affecting its primary vector, the green peach aphid. While heat waves around 30°C can negatively impact aphid populations, the optimal temperature for green peach aphid reproduction is 26.7°C, suggesting that warmer conditions could enhance vector migration and host plant approach, potentially increasing PVY transmission [111].

9.2 Effect of CO_2 on PV

Plant viruses, including Potato Virus Y (PVY), interact with their hosts under the influence of environmental conditions such as temperature and CO_2 levels, which affect plant physiology. These environmental factors can alter the carbon to nitrogen ratios, growth rates, morphological development, and the regulation of molecular pathways responsible for plant responses to both biotic and abiotic stresses [112,113,114,115,116]. Studies on PVY have shown that higher CO_2 levels can lead to decreased viral coat protein levels in leaves, suggesting a suppression of virus spread. The build-up of phenylpropanoids, like CGA and coumarins, under elevated CO_2 conditions may help confine the virus earlier [113]. Research by [117] revealed that elevated CO_2 conditions could mitigate the negative impacts of PVY infection in tobacco plants, by increasing aboveground biomass without significantly affecting total non-structural carbohydrates (TNCs) or nitrogen content. While PVY infection reduced biomass, TNCs, and nitrogen content, elevated CO_2 improved soluble protein content and offset the reduction in chlorophyll caused by PVY. There was also an observed interaction between elevated CO_2 and PVY infection on free amino acid and nicotine content, indicating that elevated CO_2 can reduce the costs of virus resistance in infected plants and delay the spread of PVY. Further studies by [17] found that the systemic levels of PVY in Nicotiana benthamiana were lower under elevated temperatures and CO_2 levels [30°C and 970 parts per million (ppm)], compared to standard conditions (25°C, approximately 405 ppm CO_2). Elevated CO_2 also affects various aspects related to aphid infestation, including growth rates, fecundity, feeding efficiency, and susceptibility of host plants to aphids, which can influence the dynamics of PVY transmission [118,119]. Research [97] reported that PVYNTN infection dramatically decreased the net photosynthetic rate and stomatal conductance without affecting intercellular CO_2 concentration. [120] noted that while atmospheric CO_2 concentrations may not directly affect aphid's ability to transmit PVY in the short term, elevated CO_2 could indirectly influence transmission dynamics by affecting plant defenses or aphid behavior, potentially leading to more efficient viral spread. [121] demonstrated that plastic bag treatments were less effective in controlling virus concentration in tubers compared to treatments with 02 plus CO_2 for 7 and 14 days, which significantly increased viral concentration, highlighting the complex interactions between environmental factors, plant physiology, and viral infection dynamics.

9.3 Effect of Relative Humidity on PVY

Studies have demonstrated a notable link between relative humidity (RH) and the severity of Potato Virus Y (PVY) infection in potato crops.

Higher levels of relative humidity have been consistently associated with an increase in PVY disease severity. Specifically, a RH range of 50–60% has been identified as conducive for the proliferation of PVY and Potato Leafroll Virus (PLRV) infections [122]. Furthermore, relative humidity levels of 78-84% have been shown to significantly correlate with the escalation of PVY disease severity, as evidenced by high correlation coefficients (r values of 0.98) [123]. Contrarily, observed the highest incidence of PVY under drier conditions following inoculation, compared to more optimal growth conditions. Optimum conditions for disease prevalence were noted at 80–86% RH, alongside minimum temperatures of 11–13°C and maximum temperatures of 25–28°C, with pan evaporation rates of 2-2.9 mm [124]. In further research, [58] determined that a relative humidity of 82-83% is particularly conducive to increased disease severity. It was also found that combining high temperatures (25–30°C) with high RH (80–90%) significantly boosts the transmission of PVY by 30–35%. Conversely, at 25 or 30°C, PVY transmission rates were about 50% lower when RH was maintained at 50% during both pre- and post-inoculation phases [125]. Additionally, the population of whiteflies, which serve as vectors for PVY, was observed to rise with increasing RH up to a certain point, after which it began to decline [126]. While these findings suggest that relative humidity may indirectly influence PVY prevalence through its effect on vector populations, further investigations are necessary to clarify the direct connection between RH and PVY incidence [127].

9.4 Effect of Light Intensity on PVY

Exposure to continuous fluorescent light at 4000 lux was found to have no significant impact on the transmission rate of Potato Virus Y (PVY) [125]. When comparing different light intensities, it was observed that lower light levels (270-330 uE/m2/sec) significantly increased the severity of mosaic disease caused by PVY in potato cultivars such as Shepody and Red LaSoda, in contrast to higher light intensities (100-200 uE/m2/sec) [64]. Additionally, the cultivation of removed explants in a growth environment with a 168-hour photoperiod cycle, under the illumination of fluorescent tubes at a light intensity of 2.5 umolm-2 S-1, was undertaken. Following applications of electric therapy, a high percentage of virus-free plantlets were successfully generated from meristem tips measuring 100 µm in length, with 93% success in Binella and 87% in Burren varieties [128].

9.5 Effect of Rainfall and Wind Velocity on PVY

Rainfall has an indirect effect on Potato Virus Y (PVY) dynamics, while the direct influence of wind velocity on PVY spread is minimal since the virus is predominantly transmitted via infected seed potatoes and aphid vectors. Rainfall can serve as a mechanism for depositing aphids, which are transported via low-level jet streams, onto potato crops [16]. A study spanning nine years found that 29 out of 30 instances of low-level jet occurrences, which were associated with rain events in May and June, could potentially influence aphid dispersal [129]. Despite regular precipitation patterns each spring in the studied areas, establishing a direct link between spring rainfall and the incidence of PVY in the same season proved challenging. This difficulty arises from various confounding factors such as the practice of roguing (removing diseased plants) and the variability in the timing of leaf sample collection. Moreover, aphid populations, which are crucial for PVY transmission, can be significantly reduced or even eradicated by severe weather conditions, including strong winds and heavy rainstorms, thus affecting the spread of PVY [130,131].

10. MANAGEMENT OF PVY

Managing Potato Virus Y (PVY) in potato crops presents an ongoing challenge due to its non-persistent mode of transmission and the practice of cultivating seed potato tubers across multiple generations, which elevates the risk of both primary and secondary infections by PVY [132]. In recent years, PVY has caused significant damage to potato crops, with environmental conditions playing a critical role in influencing the virus's impact. Consequently, there is a pressing need to adopt environmentally sustainable strategies and utilize resistant varieties to control the spread of PVY effectively.

10.1 Cultural method

Utilizing virus-free seed potatoes or those with a minimal occurrence of PVY can significantly reduce the sources of inoculum within a field, thereby decreasing the risk of PVY transmission [133,134]. Research in Switzerland demonstrated that elevating the planting altitude from 400 m to 800 m resulted in a 57% reduction in potato infection rates, largely due to cooler temperatures at higher elevations [135]. Implementing earlier planting and timely haulm destruction can also mitigate the risk of PVY spread [132]. Early termination of the crop's foliage reduces the period during which the plants are exposed to aphid vectors, thus lowering the likelihood of infection [133,135,136].

For effective PVY management, it is essential to eliminate all potential sources of the virus. This includes removing weeds, diseased seed tubers, and volunteer plants those sprouting from tubers or tuber pieces left in the soil after harvesting the previous crop [87]. While roguing removing visibly infected plants can contribute to controlling PVY spread, its success rate varies, with reductions in PVY ranging from 0% to 20% [137]. For border crops to be effective in preventing PVY spread, they need to be resistant to the virus. Border plants can also physically block aphid movement, serving as a barrier to their flight [138]. Straw mulching has been shown to be an effective method for controlling PVY spread [139,140,141,142]. While increasing nitrogen levels in the soil may impact overall plant growth, it does not significantly reduce the yield loss associated with PVY infections [143].

10.2 Host-plant Resistance

In the context of integrated pest management, plants have developed various defense mechanisms to ward off attacks from phytopathogens, which are instrumental in breeding resistant cultivars [144]. Utilizing the coat protein genes of PVX and PVY, [145] engineered the Russet Burbank, a leading commercial potato cultivar, to be resistant. These genetically modified plants, harboring the CP genes for both viruses, showed resistance to PVX and PVY infections through mechanical means of inoculation. Additionally, when exposed to PVY through viruliferous green peach aphids, one transgenic line exhibited resistance. Interestingly, a significant fraction (22.5%) of non-transgenic plants displayed resistance, hinting at the existence of other resistance (R) genes, possibly related to hypersensitivity, which might influence the effectiveness of resistance tests. The detection of the Ryadg gene proved to be highly effective (99.7%) in identifying PVY-resistant genotypes among both parent plants and their offspring, highlighting its utility as a genetic marker in potato breeding efforts aimed at developing PVY-resistant varieties [144]. Furthermore, three tetraploid somatic hybrid lines created by fusing protoplasts from a dihaploid Solanum tuberosum cultivar BF15 and the wild species Solanum berthaultii were evaluated for their resistance to several soil-borne pathogens, including Fusarium solani, Pythium aphanidermatum, and Rhizoctonia solani. These hybrids, named STBc and STBd, also showed increased resistance to the common strain of potato virus Y (PVYo) under greenhouse conditions [146].

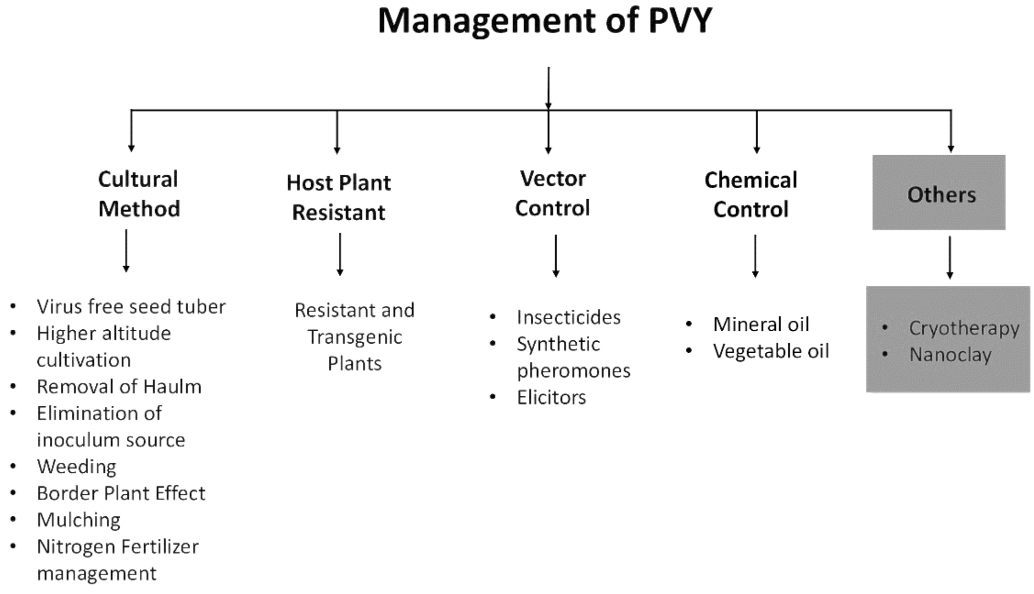

Fig. 4. Management of Potato Virus Y, [22]

10.3 Chemical Control

Applying oil sprays to potato plants has been proposed as a method to prevent the spread of Potato Virus Y (PVY). This approach has been explored in various studies [135, 147,148,149,150,151,152,153]. Comparative analysis has shown that while vegetable oil can offer some level of protection against PVY, mineral oil is generally more effective in preventing virus transmission [134,153,154].

10.4 Vector Control

Pyrethroid-based pesticides have been found to effectively reduce Potato Virus Y (PVY) transmission under controlled conditions, providing a rapid "knockdown" effect on aphids [155,156,157]. Pesticides can hinder the transmission of viruses in two primary ways: by deterring aphids through the use of substances like deltamethrin [158], altering their feeding behaviors with chemicals such as thiamethoxam, imidacloprid, pymetrozine, and fluticamid [159,160,161], and reducing aphid mobility with aldicarb [162]. However, the overall impact of insecticides on virus epidemiology is limited, as aphids typically transmit PVY prior to being affected by the insecticides [161]. Research has also shown that synthetic pheromones, specifically (E)-β-farnesene (EβF), can prevent the green peach aphid, Myzus persicae (Sulzer), from both acquiring and transmitting PVY [163]. Further investigations revealed that PVY transmission is more likely when aphids encounter EβF, as demonstrated in studies with wingless aphids, Myzus persicae and Macrosiphum euphorbiae, on tobacco plantlets [164]. The application of acibenzolar-S-methyl (Bion®), an elicitor that functions analogously to salicylic acid (SA), on tomato leaves followed by PVY inoculation, has been explored [165]. A field trial assessing Bion® for preventing PVY spread in potato crops indicated a modest reduction in virus transmission by about 14% [151]. Employing mechanical barriers, such as barrier crops and polyethylene sheeting, presents an immediate solution for managing PVY and its vectors, offering a supplementary strategy for virus control [22]).

10.5 Other Methods

Cryotherapy techniques, including encapsulation-dehydration, encapsulation-vitrification, and droplet methods, have been successfully applied to eradicate Potato Virus Y (PVY), achieving virus-free plantlet rates between 91 to 95%. In terms of biological control, applications involving Klebsiella oxytoca and biochar have demonstrated a significant reduction in both the severity and concentration of PVY. Additionally, experimental treatments involving tobacco and potato plants in greenhouse conditions resulted in notable enhancements in plant growth [166]. Moreover, the use of nanomaterials presents a promising avenue for managing PVY. Specifically, foliar applications of nanoclay have shown potential in effectively and sustainably controlling plant viral infections, including PVY [167].

11. CHALLENGES AND FUTURE PROSPECTS

The shifting patterns of pest and vector distribution, exacerbated by climate change, present significant obstacles to Potato Virus Y (PVY) management. However, this challenge also opens opportunities for devising sustainable and robust strategies for combating PVY. Future research in this area will be crucial for maintaining sustainable, resilient, and economically viable potato cultivation across all potato-growing regions worldwide. A key component of future strategies involves the adoption and enhancement of integrated pest management practices. There is a pressing need to focus on developing and implementing biological control methods to reduce reliance on chemical pesticides and mitigate the risk of developing pesticide-resistant insect populations [168]. Moreover, the demand for innovative technologies that facilitate rapid propagation of healthy plants in controlled environments is escalating, aiming to produce high-quality seeds at affordable costs [10]. Although breeding pest-resistant potato varieties is recognized as a cost-effective approach for disease management, it requires time. Nonetheless, it remains a fundamental defense against viruses and other plant diseases [169]. Advances in diploid potato breeding and the application of more precise molecular markers hold the potential to revolutionize these efforts in the future [170]. Genetic engineering for resistance to various PVY strains offers a promising avenue for long-term control of PVY, especially as new strains emerge that may circumvent resistance conferred by traditional R genes [171]. Additionally, adopting climate-smart agricultural practices, including crop rotation, diversification, and agroforestry, will play a vital role in fostering resilient agroecosystems that are better equipped to withstand PVY outbreaks.

12. CONCLUSION

Plant viruses pose a significant threat to global food security by causing widespread diseases that result in considerable direct and indirect reductions in crop yields. Among these, Potato Virus Y (PVY) stands as a major challenge in achieving high yields and quality in potato and other solanaceous crops. The ever-increasing global population intensifies the pressure on researchers, agronomists, and farmers to sustainably balance food and crop production, all while maintaining the productivity and quality of crops. Climate variables, including temperature, CO_2 levels, humidity, and rainfall, critically influence the epidemiology of PVY, affecting its transmission, replication, and spread. To effectively manage and reduce the impact of PVY, it is essential to have a deep understanding of how these climatic factors interact with the virus. Therefore, climate-adaptive management strategies should be incorporated into an integrated pest management framework, taking into account the local environmental conditions and the specific susceptibilities of potato varieties to PVY, to tailor effective control and mitigation measures.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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