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REVIEW ARTICLE

Climatic factors affecting grapevine growth and production

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Abstract

Climate resilience plays a critical role in determining the fruitfulness and yield of grapes, one of the most significant fruit crops globally. This review explores the multifaceted impacts of climatic variability on grape productivity, focusing on factors such as temperature fluctuations, rainfall patterns, humidity, and extreme weather events. Grapevines are particularly sensitive to changes in climate, which can alter phenological stages, affect flowering, fruit set, and berry development, and ultimately influence yield and fruit quality. The review synthesizes recent research on the physiological and molecular mechanisms through which grapevines respond to climate stressors, including drought, heat waves, and variable precipitation. It also examines the role of vineyard management practices in enhancing climate resilience, such as the use of drought-resistant rootstocks, canopy management, and precision irrigation. Additionally, the review highlights the potential of genetic and biotechnological approaches in developing grapevine cultivars with enhanced tolerance to climate stressors. Understanding the complex interactions between climatic factors and grapevine biology is essential for developing strategies to maintain and improve grape yield and quality in the face of climate change. The insights provided by this review will be valuable for grape growers, researchers, and policymakers aiming to mitigate the adverse effects of climate variability and ensure sustainable grape production in the future.

Keywords

extreme weather; grapes; heat waves; humidity

Introduction

Grapes and the wine industry hold significant global importance due to their economic, cultural, and social impacts. Economically, the wine industry generates substantial revenue through production, distribution, and tourism, contributing billions to national economies worldwide. Culturally, wine has been integral to social rituals, traditions, and cuisines across various societies, reflecting regional identities and histories. Additionally, the industry supports millions of jobs, from vineyard workers to sommeliers. Climate change increasingly impacts grape production, with rising temperatures, changing precipitation patterns, and extreme weather events posing significant challenges. These changes affect grape phenology, alter the timing of key growth stages, and can lead to a mismatch between grape ripening and optimal harvest conditions. For instance, warming temperatures can accelerate grape ripening, leading to higher sugar levels but lower acidity, which negatively impacts wine quality. Moreover, unpredictable rainfall and more frequent droughts stress grapevines, reducing yields and making them more susceptible to diseases.

Climate resilience in the context of grapevines refers to the ability of grapevine varieties or viticultural practices to withstand, adapt to, and recover from the adverse effects of climate change. This includes coping with increased temperatures, altered precipitation patterns, and extreme weather events such as droughts or heavy rainfall. Climatic resilience in grapevines is crucial for maintaining consistent yields, fruit quality, and overall vineyard health in the face of changing environmental conditions (1).

Grapevines are typically grown in areas with average temperatures ranging from 12 to 22°C during the growing season (1st April to 30th October in the Northern Hemisphere and 1st October to 30th April in the Southern Hemisphere) (2). The soil and climatic factors have a major impact on the crop's quality, yield, and post-harvest characteristics (3). Climate is the primary factor of grapevine quality and yield as well as global geographical distribution (4, 5). Bunch number, berry weight, yield per vine, photosynthesis rate, transpiration, and berry composition can all be significantly impacted by seasonal fluctuations (6).

The impact of rainfall on grapes is complex and affects the vine at several stages of its growth cycle. Sufficient rainfall restores soil moisture reserves, allowing for a healthy development of vines and resulting in bud break during the off-season (7). On the other hand, a lack of precipitation during this time can cause water stress, which will stop the growth and possibly affect the yield (8). Proper timing of precipitation can encourage flower bud development and differentiation during the pre-flowering stage, which may result in more fruit set and, ultimately, a higher yield (9). But continuous heavy rain at this time of year can be harmful, it reduces yield potential and causes flower abortion .

Higher yields can be achieved by supporting berry size and weight during fruit set and growth with moderate rainfall. On the other hand, too heavy or too little rain can cause bunch rot, disease pressure, and ultimately yield losses (10). Rainfall patterns close to harvest time have a significant impact on the grapes composition and overall wine quality. A balanced acidity and sugar content can be achieved with the help of light, well-timed rain. But a lot of rain before harvest can dilute the sugars, which means the wine will have less alcohol and less concentrated flavors (11).

Rainfall-related overcast conditions can significantly reduce grapevine transpiration, affecting the soil water balance (12). There is a conflict over how much rain really affects the soil water balance in the root zone. Saturation of the soil due to heavy downpours and subsequent flooding can deprive plants of oxygen and make it more difficult to absorb and transfer nutrients. Continuous water saturation of the soil may delay berry growth and veraison (13), but it may not always affect berry quality. In addition, higher springtime humidity and rainfall can cause water stress, which encourages excessive vine growth and results in a larger canopy leaf area and higher transpiration losses.

Water stress affects the development of flower clusters, resulting in fewer flower clusters and fewer berries (14). Veraison was delayed by increased precipitation during the budburst interval (15). Excessive precipitation during the growing season or in the period between veraison and harvest can lead to a number of diseases, such as bunch rot, that reduce crop yield (8, 7). Extreme precipitation events have a markedly harmful impact on yield and cause increased runoff, particularly in the event that the soil has been leveled or there has been a series of droughts (5). This results in water deficits and low yield.

Climatic factors affecting grapevine growth and production

Temperature and its influence on grapes

The optimal temperature for a grape variety refers to the range within which the grapevine can complete its growth cycle budburst, flowering, veraison (onset of ripening), and harvest under favorable conditions .

Bud break

Warmer temperatures accelerate bud break, leading to earlier flowering and ripening. Conversely, colder temperatures can delay bud break, increasing the risk of frost damage.

Flowering and fruit set

Adequate temperatures are essential for successful pollination and fruit set. Excessive heat can lead to pollen sterility, while cold temperatures can hinder pollen viability.

Ripening

Warm temperatures are crucial for grape ripening, as they accelerate the accumulation of sugars and other compounds that contribute to wine flavor and quality. However, excessive heat can lead to dehydration and sunburn.

Heat and cold stress

Grapevines thrive in specific temperature ranges, and when scorching heat waves strike, their growth and fruit development take a significant hit. This phenomenon, known as heat stress, disrupts the delicate balance of the vine's natural processes. One of the first signs of heat stress is a slowdown in vegetative growth. Shoots grow less vigorously, leaves shrink in size, and the spaces between each leaf node (internodes) become shorter. This reduced leaf area translates to a decline in photosynthesis, the vital process by which the vine captures sunlight and converts it into energy. Consequently, less sugar is available for grape development, potentially leading to a lower-quality harvest.

Cold stress is a significant challenge for grapevines, primarily affecting them during their dormant period and the critical phase of bud break. While most detrimental during these stages, its impact also extends to fruit development. Severe winter conditions can cause winter injury, damaging canes, buds, and even roots, ultimately reducing the number of shoots and overall yield. Delayed bud break due to prolonged cold temperatures can extend the vegetative period, increasing the vine's vulnerability to late frosts during flowering. Furthermore, cold stress can impair pollen viability and fertilization, leading to reduced fruit set and lower yields. Weakened by these stressors, grapevines become more susceptible to diseases, compounding the challenges faced by growers.

Sunlight

Grapes are considered short-day plants, meaning they require a specific balance of light and dark periods to initiate flowering and ripening. Insufficient light can delay ripening, leading to under-ripe grapes with higher acidity and lower sugar content. Conversely, excessive light exposure can accelerate ripening, potentially compromising flavor complexity and aroma development (16). Shade can significantly impact grapevine physiology and fruit quality. Insufficient light exposure leads to reduced photosynthesis, delayed ripening, lower flavor intensity, thin-skinned berries. While sunlight is essential for grapevine growth and ripening, excessive exposure can also have negative consequences like sunburn, water stress, accelerated ripening (17).

Carbon dioxide

The rising concentration of carbon dioxide (CO_2) in the atmosphere is a global concern with far-reaching implications for agriculture, including viticulture (17). While increased CO_2 levels can benefit plant growth by enhancing photosynthesis, the effects on grapevines are complex and influenced by various factors such as temperature, water availability, and cultivar. Positive impacts like enhanced photosynthesis, and improved water use efficiency. Negative Impacts involve reduced acidity, nutrient imbalances, and increased susceptibility to pests and diseases.

Heat stress

High temperatures can disrupt several crucial physiological processes in grapevines. Photosynthesis, the process of converting sunlight into energy, is inhibited under heat stress, leading to reduced carbohydrate production. Increased temperatures also stimulate transpiration, the plant's cooling mechanism, which can lead to water stress (18). To conserve water, plants often close their stomata, small pores on leaves, but this action also limits the intake of carbon dioxide needed for photosynthesis (19). Additionally, heat can elevate respiration rates, consuming more energy, and plants may adjust their internal water balance through osmotic adjustments. Hormonal changes, particularly in abscisic acid and ethylene levels, also occur in response to heat stress, influencing various plant processes (20).

Berry composition and wine quality

High temperatures accelerate sugar accumulation while hindering the development of acidity, resulting in wines with higher alcohol content and reduced freshness. The polyphenolic profile of grapes, crucial for wine structure and color, can also be compromised under heat stress conditions (21).

Rainfall and its influence on grapes

Rainfall quantity

Bud break and early growth

Moderate rainfall (25–50 mm/week) supplies the necessary moisture for root development and rapid shoot growth (22). In order to prevent water logging, which can inhibit root development and oxygen availability (23). On the other hand, drought stress causes restricting shoot growth and possibly affecting yield (24). Recall that certain grape varietals are drought tolerant and require less water at this stage.

Flowering and fruit set

A humid microclimate produced by light rain may improve fruit set by aiding in pollen dispersal (25). On the other hand, too much rain ruins the process by destroying the flowers and making pollination difficult, which ultimately results in a lower yield.

Fruit development and ripening

Consistent berry growth and sugar accumulation are supported by steady, moderate rainfall (20–30 mm/week), which guarantees the best possible grape quality (26). Rainfall-induced evaporation of grape skins can reduce the sugar level of ripening grapes, affecting the final juice's overall sweetness and body. This can be especially harmful to grape varietals meant for the production of premium juice (27).

Rainfall intensity

Studies indicated that rainfall intensity and yield have a complicated relationship that is frequently represented by an inverted U-shaped curve. While both insufficient and excessive rainfall can result in yield reduction and unfruitfulness, moderate rainfall encourages yield (28–31).

Mechanisms of rainfall impact

Impact on the physiological process

Photosynthesis

Rainfall that is moderate (25–50 mm/week) has two drawbacks. It supports photosynthesis by giving readily available water for transpiration (30). This guarantees effective sugar production, which is essential for berry growth, bud development, and general vine health. However too much rain can saturate the soil, reducing its ability to absorb nutrients and oxygen, which in turn affects photosynthesis (17). On the other hand, drought stress (inadequate rainfall) causes stomata to close, decreasing CO_2 uptake and impeding photosynthesis, which has a detrimental effect on fruit set, berry size, and sugar content (31).

Water stress

A moderate amount of rainfall keeps the soil at its ideal moisture level, preventing excessive water loss while balancing water requirements and preventing extreme stress. This permits effective gas exchange and transpiration for photosynthesis. This equilibrium is changed by prolonged drought stress, which drastically reduces photosynthesis and affects yield (31). Even in situations where there is an abundance of water, excessive rainfall can amplify water stress by saturating the soil and reducing oxygen levels (17.

Nutrient uptake

Nutrients are dissolved and transported by moderate rainfall, which makes them easily absorbed by roots. Too much rain causes nutrients to be lost below the root zone, which lowers their availability and may result in deficits that affect the health of the vine and the quality of the fruit. Even when nutrients are present, drought stress can reduce the amount of water available for nutrient transport, aggravating deficiencies.

Soil characteristics

Plant oxidative stress may result from flooding, brought on by excessive rainfall. The amount of oxygen transported from the leaves to the roots becomes insufficient due to oxygen consumption and strong gas movement resistance in conditions where the roots are saturated with water. The aerobic respiration of the root is difficult when the oxygen content is in a reduced state (32). Many negative effects on plants and soil in vineyards, especially those with little soil cover, as well as their surrounding ecosystems, can result from heavy precipitation events. Raindrops have a stronger effect on bare soil because they weaken and impair the soil aggregates, making the soil more erosive and facilitating the development of crusting on the soil surface (33).

Humidity and wind

High humidity levels create an ideal environment for the proliferation of fungal diseases such as powdery mildew and downy mildew. These diseases can cause severe damage to leaves, shoots, and berries, reducing yield and compromising grape quality. Conversely, excessively low humidity can lead to dehydration and water stress, impacting vine growth and berry development. Wind can have both beneficial and detrimental effects on grapevines.

Moderate wind can help to dry foliage, reducing the incidence of fungal diseases. Additionally, wind can enhance photosynthesis by increasing CO_2 exchange. However, strong and persistent winds can cause mechanical damage to vines, resulting in reduced yield and increased susceptibility to pests and diseases. Furthermore, excessive wind can desiccate vines, leading to water stress (17).

Extreme weather

Frost can cause significant damage to grapevines, particularly during bud break and flowering stages. Low temperatures can lead to tissue damage, flower abortion, and reduced fruit set. Hailstorms can inflict severe physical damage to grapevines, causing defoliation, shoot breakage, and berry damage. This can result in reduced yield, delayed ripening, and increased susceptibility to diseases and pests. Prolonged heat waves can lead to excessive water loss, reduced photosynthesis, and heat stress in grapevines. This can result in sunburn, berry cracking, reduced berry size, and altered grape composition, impacting wine quality (18).

Physiological and molecular responses to climate stress

Grapevines are susceptible to various climatic stresses, each with distinct physiological impacts. Water stress, caused by drought, triggers stomatal closure, reduced photosynthesis, and increased abscisic acid levels, leading to smaller berries, lower sugar content, and higher acidity. Heat stress inhibits photosynthesis, accelerates respiration, and disrupts cellular processes, resulting in smaller berries, altered sugar-acid balance, and changes in flavor compounds. Cold stress, primarily frost, causes cellular damage, impacting bud break, flowering, and fruit set. Water logging deprives roots of oxygen, damages them, and hinders nutrient uptake, leading to reduced vine growth, decreased fruit set, and heightened disease susceptibility (34). Grapevines exhibit intricate molecular responses to counteract the challenges posed by climatic stress. When exposed to heat, they synthesize heat shock proteins to protect cellular structures and up regulate antioxidant genes to combat oxidative damage. Photosynthesis and carbohydrate metabolism are also affected. In response to cold stress, grapevines produce cold acclimation proteins to enhance freezing tolerance while activating genes involved in lipid metabolism and antioxidant defense. Drought conditions trigger the expression of genes related to ABA synthesis, leading to stomatal closure and reduced water loss. Additionally, osmolyte accumulation and antioxidant production are activated to maintain cellular balance. Water logging induces the expression of genes associated with anaerobic metabolism, ethylene biosynthesis, and antioxidant defense to cope with oxygen deprivation (35).

Vineyard management practices for enhancing climatic resilience

Effective vineyard management is crucial for building grapevine resilience to the escalating challenges posed by climate change. Implementing a combination of agronomic practices can significantly enhance the ability of grapevines to withstand extreme weather events and maintain productivity. Canopy management techniques, such as leaf removal and shoot positioning, optimize light interception and air circulation, reducing the impact of heat stress and diseases. Soil management practices, including cover cropping and organic matter incorporation, improve soil structure, water retention, and nutrient availability, bolstering drought resilience. Precision irrigation systems, guided by soil moisture sensors and weather data, ensure efficient water use and prevent water logging. Careful cultivar selection, considering factors like heat tolerance, cold hardiness, and disease resistance, is essential for adapting to changing climatic conditions. Moreover, integrated pest management strategies minimize reliance on chemical inputs, promoting vineyard ecosystem health and reducing the vine's vulnerability to stress.

Genetic and biotechnological approaches

Genetic improvement is a cornerstone in developing grapevine cultivars with enhanced resilience to climate change. Traditional breeding methods have been employed for centuries to create varieties adapted to specific environmental conditions. However, recent advancements in molecular genetics and genomics have accelerated the breeding process. Marker-assisted selection (MAS) enables breeders to identify and select desirable traits, such as drought tolerance, heat resistance, or cold hardiness, more efficiently. Genomic selection, utilizing high-throughput genotyping and phenotypic data, further enhances the accuracy of selection. Additionally, genetic engineering offers the potential to introduce specific genes from other organisms, conferring novel traits like enhanced stress tolerance. While this technology faces regulatory challenges, it holds promise for developing climate-resilient grape varieties in the future.

Biotechnology offers innovative tools to enhance grapevine resilience to climate change. Tissue culture techniques enable rapid clonal propagation of superior genotypes, preserving valuable genetic resources. Additionally, in vitro selection can be used to identify and select somaclonal variants with improved stress tolerance. Transgenic technology, while facing regulatory hurdles, holds immense potential for introducing specific genes conferring desired traits like drought resistance, heat tolerance, or disease resistance. Genome editing techniques, such as CRISPR-Cas9, provide precise modification of the grapevine genome, allowing for targeted improvements in stress tolerance without introducing foreign DNA. These biotechnological approaches, when combined with traditional breeding methods, can accelerate the development of climate-resilient grape cultivars (36).

Emerging technologies

The viticulture industry is increasingly adopting innovative technologies to address the challenges posed by climate change. Precision viticulture, utilizing advanced data analytics and remote sensing, enables precise monitoring of vineyard conditions, optimizing resource management and improving grape quality. Drones and satellite imagery provide valuable insights into vineyard health, water stress, and yield potential. Robotics and automation are being employed for tasks such as pruning, harvesting, and weed control, increasing efficiency and reducing labor costs. Additionally, the integration of artificial intelligence and machine learning algorithms is revolutionizing vineyard management by predicting disease outbreaks, optimizing irrigation schedules, and identifying optimal planting sites. These emerging technologies offer promising solutions for building climate-resilient vineyards and ensuring the sustainability of the wine industry (37).

Climate models in predicting future challenges

Climate models are indispensable tools for understanding and projecting future climate conditions. These complex computer simulations incorporate physical, chemical, and biological processes to replicate the Earth's climate system. By analyzing historical data and simulating various greenhouse gas emission scenarios, climate models provide valuable insights into potential temperature increases, precipitation patterns, extreme weather events, and sea-level rise. This information is crucial for assessing the potential impacts on agriculture, water resources, ecosystems, and human societies. While climate models have limitations and uncertainties, they serve as essential guides for policymakers, researchers, and industries to develop adaptation and mitigation strategies.

Conclusion

The impact of climatic resilience on the fruitfulness and yield of grapes is a critical area of study, especially in the context of global climate change. This review has highlighted the complex interplay between various climatic factors such as temperature fluctuations, rainfall patterns, humidity, and extreme weather events and their effects on grapevine physiology, phenology, and productivity. The evidence suggests that while grapevines are highly adaptable, their productivity is significantly influenced by climatic conditions, necessitating the development and adoption of climate-resilient practices.

Enhancing the climatic resilience of grapevines involves a multifaceted approach, combining advanced vineyard management practices, such as the use of drought-resistant rootstocks, precision irrigation, and canopy management, with innovative genetic and biotechnological strategies aimed at breeding more resilient cultivars. Moreover, regional adaptation strategies, tailored to specific climatic challenges, are essential for maintaining grape yield and quality across diverse viticultural regions.

Looking forward continued research into the physiological and molecular mechanisms underlying grapevine responses to climate stressors will be crucial in developing more effective resilience strategies. Additionally, the integration of climate models with viticultural practices can provide valuable insights into future challenges and help guide the industry towards sustainable grape production.

In conclusion, building climate resilience in grapevines is not just a scientific imperative but also a practical necessity for ensuring the long-term viability of the global grape industry. By adopting a proactive and informed approach, grape growers can mitigate the adverse effects of climate variability and safeguard the future of viticulture.

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Authors' contributions

NM has written the whole review. SS corrected and suggested some changes in this review. IM, MD and RJ reviewed the paper.

Compliance with ethical standards

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Supplementary data

Supplementary Table 1. Optimal average annual temperature for different grape varieties

Supplementary Table 2. Variations exist in the ideal amount of rainfall intensity based on grape variety, soil composition, and local climate

Supplementary Table 3. Advantages and disadvantages of rainfall on grapes

Supplementary Fig. 1. Climatic factors impact on grapevine growth and production

Supplementary Fig. 2. Impact of rainfall on grapes

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