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Management of abiotic stress in grapes (*Vitis vinifera*) - a review

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Abstract

Since viticulture is highly dependent on weather and climate, several climate change projections have been generated with the expectation that they may worsen the distribution of grape-growing regions in the years to come. Abiotic stress factors such as drought, salinity, temperature, hailstorm, and rainfall can restrict the growth and productivity of grapevines, as well as affect their quality and composition. Especially during critical developmental stages such as flowering, fruit set and ripening. This paper focused on review of current knowledge available on the effects of these stressors on grapevine physiology, development, and yield as well as the strategies and techniques to mitigate them. The paper provides a comprehensive overview of the management of abiotic stress in grapes and the challenges and opportunities for future research and grape growers can minimize the negative impacts of abiotic stresses.

Key words: Abiotic, Climate change, Mitigation, Stress, Salinity, Drought, Viticulture

Grape (*Vitis vinifera* L.) is a major horticultural crop grown on an area of 7.2 Mha, with the production of 27.9 million metric tonnes worldwide. Major grape producing countries are China, Italy, France, Spain, USA, Turkey, and India (OIV, 2024). According to II advance estimates of 2023, grape cultivation in India was on an area of 1,75,000 ha while production was 3896 thousand tons (Anonymous, 2024). Worldwide, grape is being grown mainly for wine, and less for fresh consumption, and juice. However, under Indian conditions, grape is cultivated mainly for table purpose and raisin making while minimum quantity is being consumed for wine and juice. Primarily, grape crop is from temperate region; however, it has been widely adopted in tropical and subtropical conditions. Indian viticulture thus has become unique as grape is now being grown from tropical to temperate climate.

Grape is a high value export-oriented fruit crop which has gained significance in tropical climatic conditions in the country due to location specific suitable modifications. However, during the last five years, it is seen that the grape industry is experiencing major setback due to changes in climatic conditions. The grapevine is facing the problems of unseasonal rains, hailstorm, cold waves during berry development stages and, high temperature during fruit bud development stage. Drought, salinity, temperature, unseasonal rains, flood are some of the major examples of abiotic stresses found around the world (Tester and Bacic, 2005). The global distribution of grapes is severely constrained by a variety of abiotic stresses. Only water deficiency has been successfully employed to the flavor and quality features of grape berries (Roby *et al.,* 2004, Chapman *et al.,* 2005). Reduced shoot vigor and competition for carbon resources (a change in the source to sink relationship) are two factors that contribute to this effect. Scientific evidence sharply states that climate change represents a dominant challenge for viticulture in the upcoming decades (Hannah *et al.,* 2013).

Summer stress generally refers to a variety of abiotic pressures that are exacerbated during the summer, such as water shortage, intense sunshine, and high temperatures (Cramer *et al.,* 2011). Given that many biochemical processes are light and temperature sensitive, it is crucial to understand the link between grape cluster temperature and solar exposure to understand grapevine metabolism (Spayd *et al.,* 2002). A severe drought causes a water deficit in the plant that lowers cell turgor, which causes stomata to close and cells to grow less, limiting leaf surface and photosynthesis per unit area. Understanding abiotic stress factors, it is essential to identify the specific factors that grapes are exposed to weather in a particular region.

This understanding will help in devising appropriate strategies for management. For instance, areas with high temperatures might require different strategies to overcome heat stress, while regions with poor soil quality might need nutrient management techniques. Extreme temperatures (both high and low) can impact grape production. Using strategies like shading, windbreaks, and selecting appropriate grape varieties for the local climate can mitigate temperature-related stress. In areas

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with saline soils, salinity stress can occur. Soil amendment techniques, proper irrigation scheduling, and salt-tolerant rootstocks can help to manage this stress. Choosing appropriate rootstocks that are tolerant to specific stress factors can enhance the plant's ability to cope with stress conditions. Grafting grapevines onto stress-tolerant rootstocks is a common practice. Proper canopy management during each season under tropical condition can ensures adequate light exposure, air circulation in the canopy, and reduction in disease incidence.

This review on management of abiotic stress in grape cultivation aims a holistic approach by implementing appropriate strategies and techniques. Grape growers can minimize the negative impacts of abiotic stressors leading to improved grape quality and overall vineyard productivity. The details outlines are as below.

Effect of high temperature

In India, grapes are mainly grown under tropical condition with high temperature reaching to 44^{0}C in some areas during fruit bud differentiation stage. During this stage, the high temperature affects basic physiological processes and growth of the grapevine. Although the grapevine needs a base temperature of 10°C to begin its vegetative cycle, it is also known that if the high-temperature threshold rises at crucial developmental stages the detrimental effects take place affecting the photosynthesis, berry size, sugar accumulation, and ripening. According to Kun, *et al.* (2018), 25 to 35°C is the ideal photosynthetic temperature for grapevines development. Above 40°C temperatures have an adverse impact on photosynthesis, mostly because they disturb the system that allows for photosynthesis.

According to Keller (2020), yield of grapevine depends on number of buds, bud fertility, number of berries per bunch and average berry weight. During the floral initiation period, high temperatures (>35^{0}C) was able to produce infertile buds (Keller, 2020). The mid-day temperature is high with temperatures ranging from 35 to 40^{0}C during blooming had a negative impact on fruit set and ovule fertility resulted in less berries per cluster (Greer and Weston, 2010). As per Pagay and Collins, (2017), extreme temperature (>35°C) during the flowering phase had a negative impact on fruit set (-48 to 38%) and eventual yield (-27%). Temperature variations have a significant impact on flowering and fruit set.

Continuous increase in temperature may result in peculiar development pattern of vines resulting in early flowering and berry softening.

This early season crop may lead towards the warmest period of season thus affecting grape yield and quality measured in terms of sugars, organic acids, phenolic compounds etc. (Keller *et al.,* 2010). Van Leeuwen and Destrac-Irvine (2017) observed that increase in temperature is predicted to diminish the acidity and increase the sugar content of grape berries, leading to unbalanced wine with greater alcohol content and lacking in freshness and aromatic complexity. High temperatures also tend to decrease anthocyanin content. During the maturation stage of most of the grape varieties, optimum temperature between 20-22^{0}C is ideal for formation of aroma compounds (Blancquaert, *et al.*, 2018). At temperatures above 30°C, colour formation is reduced, and above 37°C, grape colour is diminished and flavour element volatilization is increased (Neethling *et al.,* 2012). Anthocyanin is the main coloring compound found in grapes, during the high temperature condition reductions of delphinidins, anthocyanins, petunidin and peonidin-based anthocyanins in grapes is observed (Bernardo *et al.,* 2018).

High temperatures have an impact on the sugar-acid balance ratio as well. Increased temperatures have the potential to facilitate the buildup of sugars and the concurrent deterioration of organic acids, with the acidity being more severely impacted than the sugars. As a result, grapes cultivated in warmer climates have lower acidity for the same sugar level. The grape growing areas of Maharashtra and Karnataka experiences the high temperature during fruit bud differentiation after foundation pruning resulting into reduced fruitfulness of grapevine. During bunch development period after forward pruning, the high temperature hampers the berry development. In addition, it also reduces the quality as the berry colour changes from green to yellow which does not fit into the quality standard for export. Under the high temperature condition, total soluble solids increase at faster rate in grape berries.

Mitigations of high temperature stress

In grape vineyard of tropical region, the growth and developmental stages coincides with high temperature. Extreme high temperature leads to burning of shoot tips, scorching of leaf margins, leaf drying, etc. Reduction in internodal length thereby reducing the shoot vigor is some of the major effects leading to reduced storage of food material in the current seasons shoot. Crop load and leaf area influence the leaf to fruit ratio, we can lower this ratio by reducing leaf area through shoot pruning (Santesteban *et al.,* 2017). Leaf removal is a basic viticulture technique used for vineyard canopy control. Leaf removal is done on basal leaves to enhance cluster microclimate, increase fruit composition, and lower disease pressure (Smith and Centinari 2019).

Minimum pruning is a viticultural technique with a wide range of potential applications, especially in warmer climates where one of its most notable effects is to delay berry ripening and create a cooler ripening environment for the grape development, which favours the accumulation of anthocyanins and preserves grape acidity. Minimum pruning is also a low-cost, time and money intensive method that produces high yields (Clingeleffer 2010). According to Keller, (2010) light is the most important part of photosynthesis, and the quantity and quality of light have an impact on the rate at which photosynthesis occurs. Novello and de Palma (2013) studied the shading nets over grapevines and concluded that shading nets decrease the amount of photosynthetic photon flux at the leaf surface that can be used for the photosynthetic process, which may delay fruit ripening. These effects are likely explained by the fact that the shade nets can reduce the temperature of the fruit and the canopy by up to 7^0C (Lobos *et al.,* 2015). Das and Raghavendra (1979) found that use of antitranspirants decreased transpiration losses, conserving water loss and by consequence, mitigating fruit shrinking.

Due to the impact of high temperatures and heat stress on canopy physiological processes, sunburn, yield, and berry quality, the use of this method in viticulture has recently increased (Frioni *et al.,* 2019a, 2019b). Canopy management practices, such as increasing leaf growth during hot period to provide shade for the fruit, removing leaves from the southeast or eastern side to capture morning sunlight, and positioning shoots on the northwest or western side to protect fruit from the intense afternoon heat, help reduce heat stress. Additionally, managing water to maintain varying levels of leaf cover plays a key role in preventing heat damage. Shade nets are also commonly used to minimize heat injury, particularly by growers of export-quality grapes (Sharma *et al.*, 2013).

Effects of low temperature

Low temperature can reduce crop yields, by damaging the vine, the development of secondary issues like crown gall or even the complete death of the vine (Quamme, 1986). At temperatures of 4°C and below, roots are susceptible to freezing damage (Okamoto *et al.,* 2000). Deep soil freezing can occur because of factors such a lack of snow cover, extremely dry soil, and persistently low temperatures, which can also cause root damage. Root damage can also affect the trunk and canes, which can be seen during the growing season when the vine fails to grow or sometimes collapses. Wolfe (1991) reported that low temperatures additionally restrict plant species, but they may recover rather quickly once they return to warmer climates. According to Buttrose (1969), temperature drops severely inhibit grape shoot and root growth as well as fruiting yields.

Mitigations of low temperature stress

In India, Nashik district of Maharashtra state has major grape cultivation used for export purpose. In this region, mainly white seedless grape varieties are grown. In some of the grape growing pocket of this district, the grape vineyard during berry development stage (10-14 mm berry size) faces low temperature thereby leading to drying of leaves, leaf scorching/burning, sunscald symptoms on developing berries, etc. This hampers the physiological processes of grapevine thereby reducing the crop yield. In addition, the hailstorm is also being experienced in these areas resulting into berry damage/cracking. In these areas, use of plastic on the vineyard will help to increase canopy temperature as well as hail net so as to reduce the chances of crop losses. Removal of any barriers that may restrict airflow on frost-prone areas, such as shelterbelts and overgrown grass along fence lines can help (McCarthy, 1997).

According to Rahemi (2016), several cultural practices such as appropriate slope, good soil and drainage, cold air drainage, and site selection, may be able to shield vines against winter damage. While some farmers cover the crown and root sections of their planting rows with straw mulches, others cover every part of the vegetative parts of the planting rows with geotextile materials (white blanket). Depending on the kind of soil, the grape growers are either burying the entire vine with soils or hill the soils on planting rows to a height of 20 to 25 cm (to cover the graft unions and lower the trunk) before the soil freezes (re-hilling if the soil washed away by a severe storm). American grape varieties including *Vitis labrusca* L., *Vitis aestivalis* Michx., and *Vitis riparia* Michx. have several cold tolerance genes, and these species exhibit relatively stronger cold hardiness than *V. vinifera* (Fennell 2004).

Among these, the best approach to cultivate grapes in a cold climate is to select rootstocks with the right vine balance in addition to cold-hardy cultivars. Within cold climate rootstock breeding programs, one of the primary selection criteria is cold hardiness (Rahemi, 2016). A study conducted by Guo *et al.* (1987) reported taht in regions where soil temperatures drop significantly during the winter, grape rootstock can help prevent root cold injury. According to Rahemi *et al.* (2022) delayed pruning technique involves pruning in two stages: an initial lighter pruning when the vines are fully dormant followed by a final bud-count pruning after the risk of frost has completely passed is beneficial for cold injury.

Effects of drought

Under tropical conditions, the vine is pruned twice in a year (once for fruit bud differentiation and second for fruits). Water requirement of a grapevine varies with the growth stages with minimum quantity requires during fruit bud differentiation stage (31 to 60 days after foundation pruning). Water deficiency has a several kinds of effects on vegetative and productive growth stages. Prior to slowing down the growth of the main shoot and controlling stomata opening, the initial physiological reaction to mild water deficiency stress is a reduction in shoot growth, which mostly affects lateral/secondary shoots (Lebon *et al.,* 2006; Pellegrino *et al.,* 2006). One of the earliest signs of water shortage is a reduction in early plant development. The physiological behavior of vines, as well as the quantity and quality of grapes and wines, are all significantly influenced by the plant water status (Baeza *et al.,* 2019).

Keller (2010) observed that when the water deficit increases, the vine begins to close its stomata (reduce stomatal conductance) to reduce water loss through transpiration which lowers photosynthesis. Apart from impairment of carbon metabolism, drought can also influence nitrogen metabolism and photosynthesis through reduced activity of nitrate reductase (Bertamini *et al.,* 2006). Insufficient irrigation water caused by a drought leads to decreased fruitfulness, consequently reducing the yield of table grapes (Somkuwar *et al.,* 2014). The berry quality of red grapes is improved by a mild water stress which decreases berry weight and titratable acidity while increasing TSS, total anthocyanin, and phenolic contents (Romero *et al.,* 2010). This reaction appears to be influenced by the rootstock/cultivar combination as well as by the soil and climatic conditions. Ojeda *et al.* (2002) subjected Shiraz grapevines to three levels of water deficit and found that the reduction in berry size resulted in an increase in the concentration of phenolic compounds in the berry skins. However, the timing and intensity of the stress could have a negative impact on the concentrations of phenolic compounds.

Hochberg *et al.* (2015) discovered that depending on the phenological stage, water stress altered the polyphenol metabolism of Shiraz and Cabernet Sauvignon, causing the buildup of stress-related metabolites including proline and ascorbate. A lot of research has been done to learn how water scarcity affected the physiology and quality of berries. According to Ojeda *et al.* (2001), the initial growth phase's early water deficits have the greatest effect on berry size and consequently the yield. It does not affect the rate of cell division but slows down cell expansion in the berry. Zhang *et al.* (2006) reported that the final berry size is less affected by water deficit throughout the ripening period, perhaps because of a change from symplastic to apoplastic osmotically driven sugar unloading via the phloem.

Mitigations of water stress

Since the water deficit is the main limiting factor, increasing water use efficiency, survival potential, growth capacity, and scion tolerance to stress conditions, rootstocks might play a significant role in preventing crop loss (Meggio *et al.,* 2014). According to Flexas *et al.* (2009), the rootstocks Lider 116-60, Ramsey, 1103 Paulsen, 140 Ruggeri, Kober 5BB, and Richter 110 confer to scion increased drought tolerance. Galmés *et al.* (2007) also showed that the expression of the aquaporins genes in 110 R differs between the leaves and the roots. Specifically, they showed that the expression of aquaporins upon water stress was low in the leaves to reduce transpiration and increased in the roots to increase water uptake. In times of water stress, stomata also play a crucial role in controlling water loss, and stomatal closure is one of the first reactions to a water shortage (Damour *et al.,* 2010).

Phytohormone accumulation is one of the factors that cause stomatal closure. One of the most researched hormones in plants that respond to water stress is abscisic acid (ABA) and its synthesis is one of the quickest abiotic stress responses in plants. Its buildup in leaves is associated with stomatal closure, which eventually limits cellular growth by reducing water loss (Serra *et al.,* 2014). To improve production efficiency and profitability while minimizing the negative effects of global warming, many precision viticulture tools can integrate cutting-edge techniques like artificial intelligence, sensors, decision support systems, etc. with the findings of field and laboratory studies. Thermal imaging using remote sensing can be a helpful technique for estimating variations in water status throughout vineyards, due to its capacity to measure canopy temperature, which in turn affects transpiration and ultimately plant water status (Santesteban *et al.* 2016).

Low planting density could be one of the strategies to improve drought tolerance and reduce vine competition. Pieri *et al.* (2012) established a model of the water balance and suggested that an ideal low-density system designed to adapt to future water scarcity. One strategy to deal with future temperature change may be changing the orientation of rows. In most of the tropical and subtropical conditions, different irrigation techniques are being used such as partial root zone drying technique, sub-surface irrigations, and regulated deficit irrigation improved water used efficiency without affecting productivity and quality. According to Upadhyay *et al.* (2006), application of mulches and antitranspirants (anti-stress agents) led to 25% water savings in surface drip-irrigated vines. Likewise, utilizing mulching and an anti-stress (acrylic polymer) can also achieve 25% reduction in water use for surface drip-irrigated vines. Alguacil *et al.* (2009) suggested that subsurface irrigation is beneficial in water scarcity regions, which can improve yield and quality of fruits and reduces the cost of cultivation. Use of mulches on bunds can help to reduce the evaporation losses from soil. Organic as well as inorganic mulch will be useful under specific condition. However, the availability of salts in irrigation water may affect the vegetative growth. In addition, the water loss from leaf through transpiration is more during high temperature. Under such conditions, the spray of antitranspirants at different vegetative growth stage may help to reduce the losses.

Effects of flood

The grape vineyard established in low lying areas may suffer the yield losses due to flood. Flooding can result from intense localized rainfall or a gradual flow of flood waters across the terrain, or a combination of both factors. Regardless of the cause, it is crucial to consider the duration and timing of the flooding. When flooding occurs in well-drained soil types, where water typically recedes within one or two days, it typically has minimal impact on vine growth. However, in areas where flood waters take longer to recede, either due to soil characteristics or the volume of water, certain problems may arise.

Flooding certainly has adverse impacts on plant structure, function, and chemical processes. It can lead to damage of roots and result in a decrease in fruit yield (Jogaiah, 2023). The primary issue plants face during flooding is a lack of oxygen (O_2). Waterlogging significantly reduces oxygen availability, which disrupts plant metabolism, ultimately impacting growth and productivity. The response of grapevines (*Vitis* spp.) to waterlogging remains unclear, and the molecular and metabolic reactions of grapevine roots to low oxygen levels (hypoxia) have not been fully explored. Since cultivated grapevines are hybrids formed by combining different rootstocks and scions, the complex interactions between various genotypes and environmental factors make it difficult to completely understand the mechanisms behind flooding tolerance (Ruperti *et al*., 2019).

Flooding has various effects on grapevines. It can lead to desiccation of the shoot apex, flagging of leaves, necrotic areas on leaves, senescence of basal leaves, and regeneration of roots near the water surface (Striegler *et al.*,1993). It can also affect the growth and development of grape berries and wine production, resulting in a reduction in quantity and quality (Sophie *et al*.,2015).

Mitigation of flood

The problem of flooding in grapevines can be mitigated through various strategies. One of the major approaches is to implement physiologically based water-saving irrigation methods, such as deficit irrigation and regulated deficit irrigation, which can improve water use efficiency and berry quality (Myburgh *et al.,* 2003). Another method is to shelter grapevines from rainfall, which reduces the severity of grape diseases and increases yields (Iduna *et al.,* 2019). Proper drainage in the vineyard will also help to safeguard the root system during berry development stage. By implementing these techniques, grape growers can mitigate the negative effects of flooding and ensure the long-term productivity of their vineyards.

Effect of salinity stress

Salinity is becoming a bigger issue for viticulture production, according to major grape-growing nations, especially in some parts of Australia, Greece, Italy, India, Iran, Spain, Turkey, and the USA (Baneh *et al.*, 2014). Grape output reduced by 10% in soil with an EC of 1.5–2.5 dS m−1, by 10-15% in soil with an EC of 2.5–4.0 dS m−1, and by 20–25% in soil with an EC of 4.7 dS m−1 as reported by Ayers and West cot (1985). Growing grapes may be seriously threatened by rising soil salinization because dissolved salts in irrigation water put most irrigated vineyards especially those that are deficit-irrigated at risk (Keller, 2010).

According to Marschner (1986), plant growth is negatively impacted by salinity due to two main effects: a toxic effect whereby the concentrations of the beneficial element sodium and the micronutrient chloride in the plant's tissue reach toxic levels and an osmotic effect whereby the plant experiences an osmotic drought because of the soil solution increases soluble salt concentration. Osmotic stress caused by excessive salt exposure affects grapevine roots, reducing the plant's ability to obtain water. Moreover, the buildup of Na+ and Ci- ions in plant tissues can lead vines to display phytotoxicity. If the concentration of these ions is beyond a threshold, this might cause cellular metabolism to cease (Chaves *et al.,* 2010). Reduced stomatal conductance and photosynthesis as well as leaf burn are signs of salt stress in grapevines and are typically linked to an increase in shoot Ci- rather than Na+ concentration in plant tissues (Walker *et al.,* 1997). The physiology of grapevines is negatively impacted by salt stress. It results in long-lasting drought conditions and makes it challenging for roots to take up and transfer nutrients from the soil to other areas (Jellouli *et al.,* 2010). Grattan and Grieve (1998) stated that plant growth and development are gradually restricted by salinity because it increases intracellular ionic concentrations and reduces the ability of plants to absorb essential nutrients. Salinity generally causes lower rates of CO_2 fixation, decreased dry matter accumulation, less number of bunches, smaller berries, lower yields, and decreased overall growth in grapevines (Downton *et al.,* 1990; Walker *et al.,* 2008).

There are various reasons when the yield may have decreased, including a decrease in berry size or shoot length resulting from an imbalance in the source-sink relationship, among other direct and indirect impacts (Stevens and Walker, 2002). Wine with high amounts of Na, K, and Cl has been linked to salinity derived characteristics, such as "soapy," "sea water like," and "brackish," which are viewed negatively from a sensory perspective (Mira de Orduña, 2010). High salt concentrations have an impact on several physiological functions, including lipid metabolism, protein synthesis, and photosynthetic processes (Parida and Das, 2002). Due to salt stress increase in the concentration of sodium and chloride in the leaves, as well as a decrease in the rates of leaf area expansion, dry weight of the plant and pigment contents is observed. The investigation carried out by Seemann and Critchley (1985) agreed with the leaf-area expansion rates of grapevines under salt stress.

Mitigations of Salt Stress

Many cultural practices, particularly significant water deficiency combined with salt, can be employed as coping mechanisms for changing climatic conditions. In the world's major grape-growing regions, using salt-tolerant rootstocks has been shown to mitigate the potential negative effects of salinity stress (Walker *et al.,* 2002). According to Jogaiah (2023), using resistant rootstocks that can withstand salt, such as 110R, 140 Ru, 101-14 Mgt, 1103P, etc., is another tactic to lessen the negative impacts over time. Farmers using Dogridge rootstocks as a means of overcoming abiotic challenges such as salinity and drought in majority of the grape growing regions (Somkuwar *et al.,* 2023).

The cv. Thompson Seedless, which is widely cultivated in India for both local and export markets, demonstrated reduced sodium ion accumulation and maintained yield over time when grafted on 110R (*Vitis berlandieri* x *Vitis rupestris*) rootstock (Satisha *et al.* 2010; Sharma and Upadhyay, 2008). However, Mullins *et al.,* (1996) stated the capacity of various cultivars, rootstocks, and their compatibility as well as different stock-scion combinations to limit Na or Cl entry into the shoot has been primarily attributed to salt tolerance. Inducing salt stress tolerance by lowering stress ethylene levels through the synthesis of 1-aminocyclopropane-1-carboxylate (ACC) deaminase which may enhance root growth and nutrient uptake is one way that plant growth-promoting bacterial strains can help plants.

The growth of plants can be mediated by plant growth promoting bacteria (PGPB) through many direct and indirect methods, such as enhanced nutrient availability and defense against pests and diseases. Compost, straw, green manure, organic manure, humic compounds, and biochar are examples of materials that are considered organic. To enhance soil quality and health and enable higher crop yields, these organic components can be added to saline soils. Organic acids, hydrogen ions (H+), and carbon dioxide (CO_2) are released when soil organic additions decompose (Kitila *et al.,* 2020). Suleiman *et al.,* (2021) stated that applying gypsum to crops improves their resistance to salinity stress by controlling several physiological and biochemical processes, including photosynthesis, water status, reactive oxygen species, the Na+ balance, and phytohormone levels. In addition to promoting the production, transport and secretion of proteins, antioxidants, and polyamines, sulphur also enhances a crop's response to salt stress by up-regulating genes that are very effective in mitigating a variety of abiotic stresses. During abiotic conditions like drought and salinity, some growth regulators support the maintenance of the water balance and chlorophyll content (Jogaiah, 2023).

Effect of rainfall

Indian viticulture has already been shown to be impacted by climate change. The main abiotic stressors for vineyards are unseasonal rain and hailstorms as they lead to bunch rot and berry cracking, which both lower grape quality (Kochewad *et al.,* 2021). Rainfall during flowering and fruiting is harmful. Rain during flowering causes the pollen grain to be washed away, reducing the fruit set while during pre-bloom stage it causes inflorescence rot and the incidence of diseases like anthracnose, downy mildew and bacterial blight thereby devastating the crop in the pre-bloom stage itself. Rainfall during the later stages of fruit development may wipe off a significant amount of the harvest due to the shifting climate. Fruit quality and appearance can be negatively impacted by variations in rainfall patterns. Prolonged rainfall causes an increase in humidity, which renders fruits insipid and causes skin cracking (Singh and Chhabra, 2019).

Mitigation of rainfall

Mitigation of unseasonal rains in grape vineyard can be achieved through various techniques. One such approach is to shelter the grapevines from rainfall, which has been found to reduce the severity of grape diseases and increase grape yields and farmers' income (Fei Du *et al.,* 2015). Another method is the use of a cover system that can be opened and closed automatically in response to undesirable natural events such as rain (Oana *et al.,* 2023). Additionally, irrigation, canopy shading, water nebulization, and kaolin coating have been studied as techniques to mitigate the effects of adverse weather conditions on grape yield and wine quality (Oliveira, 2018). Finally, adaptation measures such as changes in crop-management practices and varietal and land allocation changes may be necessary in the long term to mitigate the impacts of climate change on grapevines (Helder *et al.,* 2012).

Effect of hailstorm

Depending on the severity, size and timing of the hailfall, vineyards may sustain damage from hailstorms that compromise grape production each year and may even have an impact on the next season's harvest (Teodor, 2018). Hail typically severely damages leaves, branches, inflorescences, clusters, and berries, but at higher intensities, it may also injure the stems and cordons of grapevines (Dry, 1986). Hail frequently damages the entire leaf area of the vine plant, which lead to looser, smaller, and lighter clusters as well as decreased sugar and total phenolic reserves in the grapes. In addition, hail-damaged vines displayed a higher accumulation of total soluble solids (TSS) and a bigger leaf area on the lateral branches; however, there were no negative impacts on photosynthesis, berry mass, grape acidity, or fertility in the subsequent year (Petoumenou *et al.,* 2019).

According to Vinet (2001), the damage caused by hail is much more severe if it occurs during the ripening stage, when cell division is at its peak, as grapevines are not capable of healing. However, if hail falls during fruit set, when cell division is occurring inside the plant, damage caused by hail can be healed. With the hails, the microclimate in the canopy increases thereby leading to incidence of fungal diseases. There has been a significant loss of fruits and flowers due to hail damage (Bal *et al.,* 2014). Hail can cause damage to branches of scaffolds, shatter, or break shoots, and inflict injuries on fruits some of which may fall to the ground. As evidenced by grape vines where badly damaged vines did not sprout after pruning during the next season, hail damage can have a serious negative impact on a vine's health (Jogaiah, 2023). It is important to know how to take care of hail-damaged plants and try to get them back into production after a severe hailstorm.

Mitigation of hailstorm

Shoot pinching just below the hail damage and treat the plant with copper oxychloride @ 2.0 g/L water if grapes suffer hailstorm damage right after backup pruning. Mulch with antistress products increase abiotic stress tolerance, whereas subsurface irrigation reduces the amount of water needed. It is possible to shield grapes from hailstorms and other biotic pressures by cultivating them in plastic covering. Anti-hail nets have been employed as a protective tool for crops to minimize hailstorm losses, but their potential to change the tree microclimate may potentially affect the growth and quality of trees (Manja and Aoun, 2019). Shade nets might be a useful alternative in locations where hailstorms are more likely to occur. Crops protected by nylon nets against bird damage are also shielded against hail damage (Bal *et al.,* 2014).

The application of bio-stimulants exogenously through various mechanisms not only enhances plant growth and productivity but also improves yield and yield nutritional quality (Ali *et al.,* 2020). According to Petcu *et al.,* (2007), the incorporation of fertilizers containing amino acids facilitates a smoother adaptation to plant stressors induced by severe occurrences like low temperatures, hail, and water stress.

CONCLUSION

The management of abiotic stress in grapes, focusing on the effects and mitigations of abiotic stress. Abiotic stress affects the physiological processes, growth, quality, and productivity of grapevines, especially during crucial developmental stages such as flowering and ripening. This paper emphasizes the need for a wide approach to manage abiotic stress in grape cultivation, considering the local climate and soil conditions, and aiming to improve grape quality and vineyard productivity. The successful management of abiotic stress in grapes requires a multifaceted approach that integrates agronomic practices, technological advancements, and ongoing research. By combining these strategies, grape growers can enhance the resilience of vineyards, optimize grape quality, and ensure the long-term sustainability of grape cultivation in the face of environmental challenges.

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