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SUNBURN IN HORTICULTURAL CROPS: CAUSES, PHYSIOLOGICAL AND MOLECULAR MECHANISMS, AND ECONOMIC IMPACTS

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ABSTRACT
Sunburn is an important abiotic disorder affecting the productivity, quality and marketability of horticultural crops. It occurs when plant tissues receive excessive solar radiation and experience elevated surface temperatures beyond their capacity for physiological protection and acclimation. The disorder affects a wide range of fruit, vegetable and ornamental crops, although its symptoms and underlying mechanisms vary with species, plant organ and environmental conditions. In fruit crops, sunburn commonly appears as browning, bleaching, necrosis or localized surface injury, whereas in vegetables it is frequently expressed as fruit sunscald, leaf scorching and tissue necrosis. In ornamental crops, excessive radiation and high temperature may cause petal bleaching, pigment degradation, marginal necrosis, bud injury and reduced flower longevity. The development of sunburn is influenced by solar radiation, ultraviolet exposure, fruit or tissue temperature, relative humidity, water availability, canopy architecture and nutritional status. At the physiological and biochemical levels, excessive radiation and heat can disrupt photosynthesis, induce photoinhibition, promote reactive oxygen species accumulation, alter membrane stability and affect pigment metabolism. Sunburn results in economic losses through reduced marketable yield, quality downgrading, postharvest deterioration and rejection in premium markets. Recent molecular studies have further improved understanding of antioxidant metabolism, stress-responsive pathways and pigment-related changes associated with sunburn development. This review discusses the occurrence, causes, physiological and molecular mechanisms, crop-wise manifestations and economic consequences of sunburn across fruit, vegetable and ornamental crops, while identifying research priorities for understanding this disorder under changing climatic conditions.

KEYWORDS: Abiotic stress, antioxidant defence, fruit sunscald, heat stress, horticultural crops, oxidative stress, solar radiation, sunburn

1. INTRODUCTION
Horticulture plays a pivotal role in agricultural diversification, nutritional security, employment generation and income enhancement, while contributing substantially to domestic and international agricultural trade. Fruit, vegetable and ornamental crops are particularly important because of their high economic value, nutritional attributes and contribution to the livelihoods of farming communities. However, the productivity, quality and commercial value of horticultural commodities are increasingly threatened by environmental stresses associated with climate variability and climate change. Among these stresses, excessive solar radiation and elevated temperature are important environmental determinants of plant injury and physiological disorders. Sunburn is one such environmentally induced disorder that affects a wide range of horticultural crops, particularly under conditions of intense solar irradiance, prolonged heat exposure and inadequate moisture availability (Racsko and Schrader, 2011; Munne-Bosch and Vincent, 2019; Fischer et al., 2022).

Sunburn is a radiation- and temperature-associated physiological disorder that develops when plant tissues are exposed to excessive solar energy, resulting in tissue temperatures and photochemical stress beyond their capacity for physiological protection and acclimation. The disorder is particularly prevalent in production environments characterized by high solar irradiance, elevated ambient temperature, low relative humidity, prolonged heatwaves, inadequate soil moisture and hot, dry winds. Although fruits are the most commercially affected organs, sunburn injury may also occur in leaves, stems, flower buds, petals and other exposed plant tissues, depending on crop species, organ characteristics and environmental conditions. Its occurrence is governed by the combined effects of radiation intensity, tissue temperature, exposure duration, water status and the inherent capacity of plant tissues to withstand thermal and photooxidative stress (Barber and Sharpe, 1971; Racsko and Schrader, 2011; Munné-Bosch and Vincent, 2019).

Sunburn has been documented across a broad range of fruit crops, including apple (Malus domestica), mango (Mangifera indica), litchi (Litchi chinensis), citrus (Citrus spp.), pomegranate (Punica granatum), grape (Vitis vinifera),

avocado (Persea americana), banana (Musa spp.), pineapple (Ananas comosus), guava (Psidium guajava) and dragon fruit (Selenicereus spp.). The severity and expression of injury vary considerably among crops and cultivars, ranging from superficial bleaching and discoloration to browning, epidermal necrosis and extensive tissue deterioration. In vegetable crops, sunscald is frequently observed in tomato, capsicum, chilli, eggplant, watermelon, muskmelon, pumpkin and summer squash, particularly when developing fruits become exposed following inadequate foliage protection or canopy deterioration. Exposed fruit surfaces may develop pale, whitish or yellowish patches that subsequently become papery, sunken or necrotic. Similarly, leafy vegetables and leguminous crops may exhibit bleaching, marginal scorching and tissue desiccation under excessive radiation and high-temperature conditions. In ornamental crops, excessive solar exposure may adversely affect leaves, flower buds, petals and inflorescences, resulting in bleaching, pigment degradation, marginal browning and reduced flower longevity. Nevertheless, direct radiation-induced injury to floral tissues should be distinguished from other heat-associated changes in pigmentation, flower development and senescence.

The development of sunburn is not attributable to a single physiological process but involves several interacting mechanisms associated with excessive heat and radiation exposure. Barber and Sharpe (1971) differentiated three forms of sunscald, namely heat-injury sunscald, ultraviolet sunscald and photodynamic sunscald of heated tissues, based on the principal factors responsible for tissue damage. Subsequently, research on apple identified three major forms of sunburn: photooxidative sunburn, sunburn browning and sunburn necrosis (Racsko and Schrader, 2011). These forms differ in their underlying physiological mechanisms and the extent of cellular injury. Photooxidative sunburn is primarily associated with excessive light exposure and photochemical damage, whereas sunburn browning involves radiation-associated pigment degradation under elevated fruit surface temperatures. Sunburn necrosis represents more severe thermal injury involving the death of epidermal and subepidermal cells. These classifications provide an important framework for understanding sunburn development, although the expression and relative importance of individual injury mechanisms may differ among horticultural species (Schrader et al., 2001; Racsko and Schrader, 2011; Munné-Bosch and Vincent, 2019).

At the physiological and biochemical levels, excessive solar radiation and elevated tissue temperature can disrupt photosynthetic activity, cellular membrane stability, pigment composition and normal metabolic functions. High irradiance, particularly ultraviolet radiation, combined with thermal stress, can enhance the generation of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide and singlet oxygen. When ROS production exceeds the capacity of enzymatic and non-enzymatic antioxidant defence systems, oxidative damage may occur to membrane lipids, proteins, pigments and other cellular constituents. Such disturbances can lead to loss of membrane integrity, pigment degradation, tissue bleaching, browning and necrosis. The extent of injury is influenced by the antioxidant capacity, structural characteristics and stress-acclimation potential of the affected tissues (Munné-Bosch and Vincent, 2019; Fischer et al., 2022). Thus, understanding the physiological and molecular responses associated with sunburn is essential for elucidating the mechanisms underlying differential susceptibility among horticultural crops and cultivars.

The incidence and severity of sunburn are further regulated by the interaction between environmental conditions and plant architectural and physiological characteristics. Importantly, ambient air temperature alone is not a reliable indicator of sunburn risk because the temperature of exposed plant organs, particularly fruit surfaces, may substantially exceed the surrounding air temperature under intense solar radiation. Solar irradiance, ultraviolet radiation, wind velocity, relative humidity, fruit orientation, surface properties, canopy architecture and evaporative cooling collectively determine the thermal and radiation environment of developing fruits. Fruits located on the outer canopy and exposed to direct sunlight are generally more vulnerable than those protected by foliage. Similarly, sudden exposure of previously shaded fruits to intense solar radiation, particularly following canopy pruning, defoliation or branch bending, may increase the likelihood of injury (Schrader et al., 2001; Racsko and Schrader, 2011; Fischer et al., 2022). Water deficit may further aggravate sunburn susceptibility by restricting transpiration and evaporative cooling, thereby increasing tissue temperature and reducing the capacity of plants to withstand environmental stress.

The occurrence of sunburn is also influenced by crop species, cultivar, developmental stage and the structural and biochemical properties of exposed tissues. Variations in fruit skin characteristics, cuticle thickness, pigmentation, antioxidant activity, tissue water status and canopy architecture may contribute to differences in susceptibility among genotypes. For example, Lal and Nath (2021) evaluated 20 litchi cultivars under Bihar conditions and reported sunburn incidence ranging from 0 to 13.61%, with the maximum incidence in CSL-16. Symptoms appeared approximately 51–56 days after fruit set and were most severe during the final 10–15 days of fruit development. Further, Lal and Sahu (2022) demonstrated considerable genetic variability for sunburn susceptibility among litchi genotypes, with differences in cuticle thickness, fruit skin strength and fruit surface temperature associated with contrasting responses to the disorder. These findings indicate that sunburn susceptibility is not determined exclusively by prevailing environmental conditions but is also influenced by the inherent physiological and structural characteristics of individual crops and genotypes.

The economic implications of sunburn extend beyond direct physical injury to plant tissues and include substantial reductions in marketable yield, product quality and profitability. In commercial fruit production, external appearance, skin colour uniformity and freedom from blemishes are important determinants of consumer preference, market grading and price realization. Even relatively minor sunburn lesions may reduce the commercial grade of fruits, whereas severe browning, bleaching and necrosis can result in rejection from fresh-fruit markets. Furthermore, damaged tissues may become more susceptible to secondary deterioration, adversely affecting storage quality and postharvest performance. Consequently, economic losses may occur even when the affected fruits remain physiologically edible and total biological production is not substantially reduced. In ornamental crops, radiation-induced damage to petals, leaves and

inflorescences can reduce aesthetic value, flower quality and vase life, thereby affecting their commercial acceptability. Lal and Sahu (2017) reported that production losses associated with sunburn in fruit crops may range from approximately 6 to 30%, depending on crop species and seasonal conditions. Similarly, Schrader et al. (2001) highlighted substantial economic losses associated with sunburn injury in apple production. The overall economic burden includes reduced marketable production, downgrading of produce, lower selling prices and additional expenses associated with sorting, handling and postharvest losses.

The significance of sunburn is expected to increase under changing climatic conditions, particularly in regions experiencing rising temperatures, frequent and prolonged heatwaves, irregular rainfall and extended dry periods. Increasing solar radiation and temperature, in combination with low atmospheric humidity and inadequate soil moisture, may intensify the exposure of horticultural commodities to thermal and photooxidative stress. Fischer et al. (2022) emphasized that climate variability and climate change are aggravating sunburn injury in tropical and subtropical fruit crops, with substantial consequences for fruit quality and productivity. Therefore, sunburn should be considered an increasingly important constraint to sustainable horticultural production, particularly in regions where high temperatures coincide with critical stages of fruit growth and development.

Although earlier studies have investigated sunburn in individual fruit crops, Racsko and Schrader (2011) provided an extensive account of its occurrence and physiological mechanisms in apple, while Lal and Sahu (2017) reviewed management strategies for reducing sunburn injury in fruit crops. More recently, Fischer et al. (2022) examined sunburn in tropical and subtropical fruit species, highlighting its environmental determinants, physiological responses and implications for fruit production. Despite these contributions, an integrated understanding of sunburn across fruit, vegetable and ornamental crops, particularly regarding the interactions among environmental triggers, physiological responses, molecular mechanisms and economic consequences, remains important. Therefore, the present review aims to provide a comprehensive synthesis of current knowledge on sunburn in horticultural crops, with particular emphasis on its major causes, physiological and molecular mechanisms of injury, genetic and crop-specific variability, and economic implications. By integrating available evidence across horticultural production systems, this review seeks to identify important knowledge gaps and research priorities for understanding sunburn susceptibility and its consequences under changing climatic conditions.

2. Definition, Classification And Physiological Nature Of Sunburn

Sunburn is generally defined as localized injury to plant tissues caused by excessive solar radiation, elevated tissue temperature or their interaction. The extent of injury depends not only on ambient air temperature but also on the temperature reached by the exposed organ, duration of exposure, radiation intensity, tissue developmental stage and the capacity of the plant to dissipate excess energy.

2.1 Photooxidative sunburn

Photooxidative sunburn occurs when plant tissues receive excessive radiation, particularly when their capacity to dissipate absorbed energy is limited. The excess excitation energy promotes the formation of reactive oxygen species (ROS), resulting in oxidative damage to chloroplasts, membranes, proteins and pigments. Symptoms may include bleaching, discoloration and localized tissue injury.

2.2 Sunburn browning

Sunburn browning is generally associated with exposure to elevated tissue temperatures that cause biochemical changes in the epidermal and subepidermal tissues. The affected areas may initially appear yellowish or bronze and subsequently develop brown discoloration. Oxidation of phenolic compounds and changes in cellular metabolism may contribute to the development of browning.

2.3 Sunburn necrosis

Sunburn necrosis represents a more severe form of injury, generally associated with excessive tissue temperature and prolonged exposure. It involves disruption of cellular membranes, protein denaturation and irreversible tissue damage. Affected areas may become pale, brown, sunken, dry or necrotic.

These forms of sunburn may occur independently or in combination. Their relative importance depends on crop species, tissue characteristics and environmental conditions (Racsko and Schrader, 2011).

3. Major Causes And Environmental Factors Associated With Sunburn

Sunburn is a multifactorial disorder resulting from interactions among solar radiation, tissue temperature, atmospheric conditions, plant water status, canopy structure and genetic susceptibility.

3.1 Excessive solar radiation and high light intensity

Excessive solar radiation is one of the principal factors responsible for sunburn. Under normal conditions, absorbed light energy is used in photosynthesis or dissipated through photoprotective mechanisms. However, when the amount of absorbed radiation exceeds the capacity for photosynthetic utilization and energy dissipation, excess excitation energy accumulates in photosynthetic tissues. This condition promotes photoinhibition and ROS production, leading to damage to chlorophyll, proteins, cellular membranes and other components. In exposed fruits, excessive radiation may produce bleaching, yellowing, browning or necrotic lesions. Barber and Sharpe (1971) demonstrated that fruit colour can influence the amount of solar radiation absorbed by horticultural fruits. In pepper and squash, white or ivory-coloured fruits exhibited approximately 60% solar reflectivity, compared with 25–35% in dark-green fruits. Consequently, dark-green fruits developed surface temperatures approximately 10–12°C higher than those of light-coloured fruits under comparable exposure conditions. This study provides classical evidence of the relationship between fruit surface characteristics and sunscald susceptibility.

3.2 High temperature and thermal injury

High temperature intensifies sunburn by increasing the surface temperature of exposed plant organs. Fruit, leaf and flower temperatures may exceed ambient air temperature because of direct absorption of solar radiation. When tissue temperature exceeds the tolerance limits of cellular structures, membrane permeability increases, proteins become unstable and cellular metabolism is disrupted. The severity of injury depends on the maximum tissue temperature, duration of exposure, developmental stage, cultivar and acclimation status. In tomato and pepper, thermal injury may cause whitish or pale-yellow fruit lesions that subsequently become dry and necrotic. In apple and mango, exposed fruit surfaces may develop browning, discoloration and epidermal necrosis. In ornamental crops, high temperature can damage flower buds and petals. Fernandes et al. (2023) documented irreversible heat injury in field-grown dahlia, including wilting, dry leaf margins, sunscald, burning and rotting. The authors observed severe injury during periods when maximum air temperature reached approximately 35°C. This temperature should be interpreted as an observation under the experimental conditions of that study, rather than a universal injury threshold for all dahlia cultivars or ornamental crops. Furthermore, Lal *et al.* (2022) observed higher sunburn incidence (10.5%) during 2019 under high-temperature and low-rainfall conditions compared with only 1.9% in 2017, demonstrating the significant influence of temperature and soil moisture availability on disorder development. High fruit surface temperature can cause denaturation of cellular proteins, alteration of membrane structure, loss of membrane integrity and thermal death of epidermal and subepidermal cells.

3.3 Ultraviolet radiation and photooxidative damage

Ultraviolet (UV) radiation, particularly UV-B radiation (280–315 nm), is an important environmental factor contributing to radiation-induced injury in exposed plant tissues. Excessive UV-B exposure can induce photochemical damage by affecting nucleic acids, proteins, photosynthetic pigments and cellular membranes, thereby disrupting normal cellular functions and metabolic activities. It can also stimulate the generation of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide and hydroxyl radicals, and modulate the expression of genes associated with oxidative stress responses and cellular defence mechanisms. The epidermal tissues of fruits are particularly vulnerable because they represent the first line of exposure to incident solar radiation. Stratospheric ozone depletion has been associated with increased penetration of biologically active UV-B radiation (280–320 nm) to the Earth's surface, potentially increasing the risk of UV-induced injury in plant tissues (Abd-Allah et al., 2013). Under normal conditions, plants possess several photoprotective and antioxidant defence mechanisms, including the accumulation of epidermal flavonoids, anthocyanins and carotenoids, together with the activation of enzymatic and non-enzymatic antioxidant systems. These protective mechanisms help dissipate excess radiation energy, attenuate UV penetration and minimize oxidative damage. However, when the intensity and duration of UV exposure exceed the protective capacity of these defence systems, excessive ROS accumulation may result in oxidative injury, membrane destabilization, pigment degradation and visible alterations in fruit colour and appearance. The susceptibility of horticultural crops to UV-induced injury varies considerably among species, cultivars and developmental stages, reflecting differences in pigment composition, antioxidant capacity, epidermal characteristics and stress-response mechanisms. Moreover, pigment accumulation may contribute to photoprotection in certain tissues, whereas elevated temperature may independently accelerate pigment degradation or suppress pigment biosynthesis. Therefore, UV-induced photochemical injury and temperature-induced pigment degradation, although frequently occurring simultaneously under field conditions, should be recognized as related but physiologically distinct processes. The risk of radiation-induced injury may be particularly pronounced in open-canopy orchards, high-altitude production regions and areas experiencing prolonged periods of clear skies, where exposed fruits receive greater amounts of direct solar and UV radiation. Fischer et al. (2022) identified increased UV radiation, low relative humidity and inadequate foliage protection among the important environmental and orchard-related factors contributing to sunburn development in tropical and subtropical fruit crops.

3.4 Inadequate canopy cover and exposure of plant organs

Canopy architecture and foliage distribution are important determinants of fruit exposure to solar radiation and subsequent sunburn development. Leaves intercept incident solar radiation and provide physical shading to developing fruits, thereby reducing the amount of radiant energy reaching fruit surfaces. Fruits developing within a dense canopy are generally less exposed to direct sunlight than those located on the outer canopy periphery. Consequently, fruits on the southern, southwestern and western sides of trees are often more susceptible to sunburn, depending on geographical location, canopy orientation and seasonal solar movement. Excessive pruning, inadequate foliage development, premature leaf senescence, defoliation and disease- or insect-induced leaf loss can reduce canopy protection and increase fruit exposure to intense solar radiation. Similarly, inappropriate pruning practices or excessive canopy opening may suddenly expose previously shaded fruits to high radiation levels. In addition, branches may bend under heavy fruit loads, exposing fruits that were previously protected by foliage, particularly during the middle and later stages of fruit development. In vegetable crops such as tomato, capsicum, eggplant and cucurbits, premature defoliation caused by early blight, leaf spot diseases, insect damage or excessive pruning can similarly increase fruit exposure and predispose them to sunscald. Modern high-density planting systems and dwarfing rootstocks may also modify canopy architecture and within-canopy light distribution. Although these systems can improve light interception and orchard productivity, inadequate management of foliage density may increase fruit exposure and sunburn risk. Fischer et al. (2022) identified insufficient foliage cover as an important predisposing factor for sunburn in tropical and subtropical fruit crops, while Racsko and Schrader (2011) emphasized the influence of fruit exposure, canopy characteristics and cultural practices on sunburn incidence and severity. Therefore, appropriate canopy management is essential not only for optimizing light interception and photosynthetic efficiency but also for maintaining adequate fruit shading and minimizing excessive solar radiation injury.

3.5 Water stress and inadequate irrigation

Water availability is an important environmental determinant of sunburn susceptibility in horticultural crops, as it directly influences plant water relations, transpiration, evaporative cooling and the ability of plant tissues to withstand thermal stress. Soil moisture deficit can aggravate sunburn injury by reducing plant water potential and restricting transpiration-mediated heat dissipation. Under inadequate soil moisture conditions, plants partially close their stomata to minimize excessive water loss, resulting in reduced stomatal conductance and transpiration. Consequently, the capacity of leaves and the canopy to dissipate absorbed solar energy through evaporative cooling is diminished, potentially increasing tissue temperature under conditions of high atmospheric evaporative demand. Although fruit skin generally has a more limited evaporative cooling capacity than leaves, the water status of the whole plant indirectly influences the thermal environment of developing fruits. Furthermore, prolonged water deficit may suppress photosynthetic activity, disturb cellular hydration, alter membrane stability and impair antioxidant defence mechanisms, thereby reducing the capacity of plant tissues to tolerate combined radiation and heat stress. Water stress may also restrict vegetative growth and canopy development, resulting in inadequate foliage protection and greater exposure of fruits to direct solar radiation. In addition, inadequate water availability during fruit development may influence fruit enlargement, cuticular properties, epidermal integrity and antioxidant metabolism, potentially increasing susceptibility to radiation-induced injury. These interactions are particularly important in arid and semi-arid production environments, where high temperatures, intense solar radiation and limited soil moisture frequently occur simultaneously. The combined effects of water deficit, elevated tissue temperature and excessive radiation may therefore intensify sunburn development in crops such as apple, mango, citrus, litchi, tomato and capsicum. Concurrent water stress has been recognized as an important factor aggravating sunburn injury in apple and other fruit crops (Racsko and Schrader, 2011; Lal and Sahu, 2017).

3.6 Nutritional imbalance

Plant nutritional status is an important physiological factor that may indirectly influence fruit susceptibility to sunburn by regulating canopy development, cellular integrity, water relations, photosynthetic efficiency and antioxidant defence mechanisms. Deficiencies or imbalances in essential nutrients can impair plant physiological functions and alter the structural and biochemical characteristics of fruit tissues, potentially reducing their ability to withstand excessive radiation and elevated temperature stress (Munne-Bosch and Vincent, 2019; Fischer et al., 2022). Calcium (Ca) plays a fundamental role in maintaining cell-wall structure and membrane integrity, thereby contributing to cellular stability under environmental stress. Potassium (K) is involved in osmotic adjustment, stomatal regulation and the maintenance of cellular water balance, which are essential for plant responses to heat and water stress. Magnesium (Mg), as a central constituent of chlorophyll, is indispensable for photosynthesis, energy metabolism and the maintenance of photosynthetic efficiency. Similarly, boron (B) contributes to cell-wall development, membrane functioning and reproductive growth. Consequently, deficiencies or nutritional imbalances may weaken plant vigour, compromise physiological resilience and indirectly increase susceptibility to sunburn. Recent experimental evidence further demonstrates the potential role of mineral nutrition in improving sunburn tolerance. Liu et al. (2025) reported that magnesium application reduced the incidence and severity of sunburn in Satsuma mandarin and navel orange by improving photosynthetic performance, maintaining photosystem II stability and enhancing antioxidant enzyme activities, including superoxide dismutase, peroxidase and catalase. Nevertheless, nutritional imbalance should be regarded as a predisposing or aggravating factor rather than a direct cause of sunburn, as adequate nutrient supply alone cannot prevent injury under extreme radiation and temperature conditions. Therefore, balanced nutrient management should be considered an important component of integrated sunburn management to maintain plant vigour, physiological stability and stress tolerance (Lal and Sahu, 2017; Fischer et al., 2022).

3.7 Low relative humidity and hot, dry winds

Low atmospheric humidity and hot, dry winds increase evaporative demand and accelerate water loss from plant tissues. Under such conditions, exposed leaves, fruits and flowers may experience rapid dehydration, particularly when soil moisture is limited. The combination of high solar radiation, elevated temperature and low humidity is especially damaging because it simultaneously increases tissue heating and reduces the capacity for evaporative cooling. Symptoms may include leaf scorching, fruit discoloration, marginal petal drying and localized necrosis.

3.8 Greenhouse microclimate and inadequate environmental regulation

Protected cultivation can reduce exposure to adverse weather, but poorly regulated greenhouse environments may create conditions favourable for heat and radiation injury. Insufficient ventilation, inappropriate covering materials, excessive solar heat accumulation and inadequate shading can increase canopy and tissue temperatures. Greenhouse-grown tomato and capsicum may develop fruit sunscald when fruits are exposed following excessive leaf removal. In rose, gerbera and chrysanthemum, excessive radiation and temperature can affect petal pigmentation, flower development and longevity. Gradual acclimatization of plants transferred from protected to open-field environments is also important to reduce photoinhibition and leaf scorching.

4. Physiological And Biochemical Mechanisms Of Sunburn Injury

Sunburn involves a series of interacting physiological and biochemical processes. These include excessive absorption of radiation, photoinhibition, oxidative stress, membrane disruption, pigment degradation and cellular death.

4.1 Photoinhibition and disruption of photosynthesis

Excessive light energy can exceed the capacity of photosynthetic tissues to utilize absorbed photons. This results in photoinhibition, particularly when high radiation is accompanied by elevated temperature and water stress. Damage to photosystem II, disruption of electron transport and reduced photosynthetic efficiency may occur. In leaves, these

changes can result in chlorophyll degradation, reduced carbon assimilation and visible bleaching. In green fruit tissues, photooxidative damage may affect chlorophyll-containing epidermal and hypodermal cells.

4.2 Reactive oxygen species accumulation

Excessive radiation and high temperature can stimulate the formation of ROS, including superoxide radicals, hydrogen peroxide and hydroxyl radicals. At controlled concentrations, ROS function as signalling molecules; however, excessive accumulation causes oxidative damage. ROS may induce lipid peroxidation, protein oxidation, pigment degradation and damage to nucleic acids. The resulting changes compromise membrane integrity and cellular function.

4.3 Membrane damage and cellular leakage

Cell membranes are sensitive to high temperature and oxidative stress. Lipid peroxidation alters membrane fluidity and permeability, resulting in leakage of cellular electrolytes and disruption of compartmentalization. Severe membrane injury may cause localized tissue collapse, water-soaked lesions, browning and necrosis. The extent of membrane damage is an important physiological indicator when comparing sunburn susceptibility among cultivars.

4.4 Changes in pigment metabolism

Sunburn may alter the concentration and distribution of chlorophylls, carotenoids and anthocyanins. Chlorophyll degradation contributes to bleaching and changes in peel colour, whereas carotenoid accumulation may occur as part of the stress response. Anthocyanin responses are more complex because these pigments may provide antioxidant and photoprotective functions, but their biosynthesis is also sensitive to temperature. Waite et al. (2023) reported changes in pigment-related pathways during the development of mid-season sunburn in apple. They also identified molecular responses associated with antioxidant metabolism and other stress-responsive processes. In ornamental crops, elevated temperature can suppress anthocyanin accumulation and reduce the intensity of red, purple and pink flower colours (Yamagishi, 2024). Such colour changes may reduce commercial quality even in the absence of direct petal necrosis.

4.5 Antioxidant defence mechanisms

Plants possess enzymatic and non-enzymatic antioxidant systems that protect cellular structures against ROS-mediated injury. Major enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR) and other peroxidases. Non-enzymatic antioxidants include ascorbic acid, glutathione, carotenoids, tocopherols and phenolic compounds. The ascorbate–glutathione cycle is particularly important in maintaining cellular redox balance. Genotypes with efficient antioxidant systems may maintain membrane stability and reduce oxidative injury under high radiation and temperature. However, higher antioxidant activity measured after exposure does not necessarily indicate inherent tolerance; it may also represent a response to greater stress injury.

5. Economic Implications Of Sunburn In Horticultural Crops

Sunburn is an important cause of economic loss because it affects marketable yield, product appearance, quality, storage potential and consumer acceptance. Its economic consequences are particularly serious in horticultural crops in which produce is graded according to external appearance and freedom from defects. Sunburn may reduce marketable production even when total biological yield remains relatively unaffected. In tomato, capsicum, chilli, eggplant and cucurbits, severely affected fruits may become unsuitable for fresh-market sale because of bleaching, necrotic lesions, surface shrinkage and secondary decay. In fruit crops, sunburned mango, apple, citrus, pomegranate and litchi fruits may be downgraded or rejected depending on the severity and location of injury. In ornamental crops, heat injury to developing buds and flowers may reduce the number of marketable flowers per plant. Sunburn damages epidermal and subepidermal tissues, compromising the protective surface of fruits and increasing their susceptibility to moisture loss and secondary microbial infection. Consequently, affected produce may deteriorate more rapidly during harvesting, transportation, storage and marketing.

In tomato and pepper, sunscalded areas may be colonized by secondary microorganisms, resulting in further tissue breakdown and decay. In fruit crops, damaged peel may lose its protective function and increase the risk of localized deterioration. In flowers, excessive temperature and radiation may cause petal dehydration, reduced tissue turgidity and premature senescence, shortening the period of acceptable postharvest quality. In commercial floriculture, vase life is an important determinant of market value. Excessive temperature and radiation during crop growth may adversely affect flower development, tissue water relations, pigmentation and senescence. In rose, chrysanthemum, gerbera and carnation, heat-associated deterioration may result in petal fading, marginal browning, premature wilting and shortened flower longevity. Suppression of anthocyanin accumulation under high-temperature conditions can further reduce flower colour intensity and visual attractiveness (Shi et al., 2022; Yamagishi, 2024). Sunburn increases the cost of cultivation because additional protective and corrective measures may be required. These include installation and maintenance of shade-net structures, additional irrigation, use of reflective particle films, fruit bagging, canopy management, improved greenhouse ventilation and additional labour for sorting and grading. Although these measures involve additional expenditure, their economic value depends on the expected reduction in sunburn incidence, improvement in marketable yield and prevailing market prices. Economic losses caused by sunburn vary considerably with crop species, cultivar, production environment, market channel and severity of injury. Lal and Sahu (2017) reported that fruit production losses may range from 6 to 30% under different crop and seasonal conditions. This range should be cited as a broad estimate from their review and not treated as a universal loss percentage applicable to all horticultural crops.

6. CONCLUSION

Sunburn is an important abiotic constraint affecting the productivity, quality and marketability of fruit, vegetable and ornamental crops. Its development results from interactions among excessive solar radiation, elevated tissue

temperature, ultraviolet exposure, water stress, atmospheric conditions, canopy architecture and genetic susceptibility. The disorder manifests as photooxidative injury, browning, bleaching, necrosis, leaf scorching and deterioration of floral tissues, depending on the crop and affected organ. Physiological and biochemical responses include photoinhibition, ROS accumulation, membrane damage, pigment degradation and changes in antioxidant metabolism. Genetic variation in fruit pigmentation, solar reflectance, cuticle characteristics, antioxidant defence and canopy architecture contributes to differences in susceptibility among genotypes. However, direct genetic evidence for sunburn resistance remains limited in many horticultural crops, particularly vegetables and ornamental flowers. The economic consequences include reduced marketable yield, quality downgrading, postharvest deterioration, loss of premium-market value and increased production costs. Integrated management involving tolerant cultivars, appropriate canopy architecture, efficient irrigation, shade nets, fruit bagging, reflective particle films and microclimate regulation offers practical opportunities for reducing damage. Future research should integrate crop-specific physiological studies, genetic characterization, advanced phenotyping, molecular approaches and economic evaluation. Such efforts will be essential for developing resilient horticultural production systems capable of maintaining yield, quality and profitability under increasing radiation and temperature stress.

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