REVIEW ARTICLE Indian Journal of Agricultural Research, Volume 58 Special Issue: 953-961 (November 2024)

Enhancing Citrus Resilience: Strategies and Advances in Abiotic Stress Management: A Review

S.K. Gupta[1], P. Bantawa[1], S. Rai[2], S. Ali[3], J. Pradhan[1], S.B. Lama[1], R. Rai[4]

10.18805/IJARe.A-6270

ABSTRACT

Citrus, a major global agricultural crop is highly valued for its nutritional benefits and widespread consumption. However, as a subtropical plant, citrus is particularly sensitive to abiotic stresses such as salinity, drought, waterlogging, nutrient deficiency, high irradiance and cold temperatures. These stresses pose significant challenges to citriculture, reducing yield and fruit quality. Traditional methods like rootstock selection and plant breeding have been used to improve stress tolerance to some extent. Recent advancements in genetic engineering and biotechnology have enhanced our understanding of the molecular mechanisms behind stress tolerance. Identifying and isolating specific genes and transcription factors have led to novel agricultural practices that economically benefit citriculture and mitigate the adverse effects of abiotic stress. This review paper emphasizes and summarises the citrus responses to abiotic stress and strategies developed to enhance stress tolerance in citrus plants.

Key words: Abiotic stress, Citriculture, Citrus, Stress management, Tolerance mechanisms.

Abiotic stresses significantly hinder sustainable agricultural growth, posing challenges to meeting global food demand (Sah *et al*., 2016). These stresses negatively impact plant well-being and necessitate adaptive strategies for survival (Mittler, 2002). Major environmental factors affecting plant growth include light, water, temperature, minerals and nutrients (Zhu, 2016). Fluctuations in these conditions cause biochemical, physiological and morphological changes, affecting plant reproduction and yield leading to economic losses (Osakabe *et al*., 2013; De Storme and Geelen, 2014).

Citrus fruits, which are cultivated worldwide, have been known among the most highly consumed fruits as a natural source of energy, nutrients and health supplements. Various species of citrus are consumed primarily as fresh fruit, raw materials for juices or are available in canned form (Lv *et al*., 2015). Citrus-derived secondary metabolites, including phenolics flavonoids, alkaloids, carotenoids, limonoids, coumarins and essential oils, are highly valued for their bioactive properties, which include antioxidative, anticancer, cardiovascular protective and neuroprotective effects. Moreover, citrus fruits are known to be used as additives, spices, cosmetic ingredients and chemoprophylactic agents in various industrial sectors (He *et al*., 2011; Keleb and Selli, 2011).

Over the past 60 years, global citrus production has surged nearly 5.5 times. The last decade (2011 to 2021) saw the most significant increase, particularly in tangerine production, which rose by over 1.44 million tons annually. During the same period, orange production grew by 312 thousand tons per year, while lemon and lime production increased by 578 thousand tons annually. Among the leading producers, China, Brazil and India stand out. China's high productivity is primarily attributed to its substantial tangerine and other citrus fruit production.

[1]Department of Botany, Kalimpong College, Kalimpong-734 301, West Bengal, India.
[2]Directorate of Cinchona and Other Medicinal Plants, Department of Food Processing Industries and Horticulture, Mungpoo-734 313, Darjiling, West Bengal, India.
[3]Regional Research Station (Hill Zone), Uttar Banga Krishi Viswavidyalaya, Kalimpong-734 301, West Bengal, India.
[4]Department of Botany, Parimal Mitra Smriti Mahavidyalaya, Malbazar-735 221, Jalpaiguri, West Bengal, India.

Corresponding Author: S.K. Gupta, Department of Botany, Kalimpong College, Kalimpong-734 301, West Bengal, India.
Email: nbubotanysaran@gmail.com

How to cite this article: Gupta, S.K., Bantawa, P., Rai, S., Ali, S., Pradhan, J., Lama, S.B. and Rai, R. (2024). Enhancing Citrus Resilience: Strategies and Advances in Abiotic Stress Management: A Review. Indian Journal of Agricultural Research. 58 (Special Issue): 953-961. doi: 10.18805/IJARe.A-6270.

Submitted: 22-06-2024 **Accepted:** 04-09-2024 **Online:** 09-10-2024

Brazil is notable as the largest producer of oranges and the top exporter of orange juice. Meanwhile, India leads the world in lemon and lime production. Other key citrus-producing countries in 2021 included Mexico, Spain, the United States, Turkey, Egypt, Nigeria and Iran, rounding out the top ten producers (Pereira and Scherer, 2023). The citrus production has been significantly affected by both biotic and abiotic stresses (Ali and Moktan, 2014; Patra *et al*., 2017).

Citrus, typically a warm-climate fruit tree belonging to the rutaceae family thrives best in subtropical regions where seasonal changes are minimal and freezing temperatures are rare. While citrus can adapt to a variety of soil types and is tolerant of both high and low pH levels, temperature and soil moisture are the primary

environmental factors influencing the health and quality of citrus trees (Syvertsen and Hanlin, 2008). They generally do not tolerate soil flooding, drought, chilling temperature further saline or alkaline soils should always be avoided for citrus. It is evident from numerous studies that citriculture is severely obstructed by abiotic stresses, such as temperature stress (Zhu *et al*., 2011), water stress (Zou, *et al*., 2017), salt stress (Zhang *et al*., 2016), mineral nutrient stress (Liu *et al*., 2018) and waterlogging stress (Wu *et al*., 2013). This review focuses on the impacts of abiotic stresses on citrus plants and their cultivation, highlighting the roles of various biochemical factors, enzymes and genes in stress response and mitigation. It also discusses strategies adopted in citriculture to overcome the effects of these stresses on citrus production.

Impact of abiotic stresses on citrus

Salinity stress

Salinity is considered as one of the major factor affecting the crop production throughout the world (Sinky *et al*., 2024). Salinity either in water or soil represents one of the major abiotic stresses specifically in arid and semi-arid regions, which can severely limit the production of agricultural crops (Nayem *et al*., 2020; Sharma and Sachan, 2024). High concentration of salt leads to hyper osmotic stress and ionic imbalance in cellular system which consequently leads to oxidative damages. Such damages in plants are responsible for growth retardation, membrane disruption, molecular alterations and even death. For the plant to be saline tolerant, their homeostatic mechanism along with detoxification machinery must be boosted (Zhu, 2016; Alam *et al*., 2020). Citrus are typically categorised as "salt-intolerant" because irrigation with saline water results in drastic decline in their growth compared to many other crops (Prior *et al*., 2007). In citriculture, electrical conductivity (EC) values exceeding 3 dS m^{-1} and sodium adsorption ratios over 9 in saturated soil extracts are considered critical thresholds for cultivation survival (Santana-Vieira *et al*., 2016).

Salinity-induced osmotic stress occurs when the dissolved salt concentration in water is high enough to inhibit crop growth. In citrus, the indirect movement of water within leaf tissues can lead to the accumulation of Cl^- ions, which negatively impacts the transpiration rate and photosynthesis (Moya *et al*., 2003). Citrus species vary in their tolerance to salinity; their tolerance level depends on their capacity to exclude toxic Na^+ and Cl^- ions from the cellular system (Khoshbakht *et al*., 2015; Moya *et al*., 2003). A research conducted by (Hepaksoy, 2000), revealed that that fruit yield of citrus crop was reduced by approximately 13% when subjected to soil with higher electrical conductivity of the saturated soil extract. The other reported effects of salinity in citrus are decline in stomatal conductance leading to reduced CO_2 diffusion eventually, affecting the photosynthetic efficiency (García-Sánchez and Syvertsen, 2006) and elevated ion accumulation (Brumos *et al*., 2010). Though some of the citrus species are found to be salt tolerant like, Sunki mandarin (*Citrus sunki* Hort. ex Tan.), Rangpur lime (*Citrus limonia* Osbeck) and Cleopatra mandarin (*Citrus reshni* Hort. ex Tan.) while trifoliate orange [*Poncirus trifoliata* (L.) Raf.] and its hybrids such as Carrizo citrange [*Citrus sinensis* (L.) Osbeck × *P. trifoliata* (L.) Raf.] are characterized as salt sensitive as reviewed by (Hussain *et al*., 2012).

Drought stress

Given the global impact of abiotic stresses on tree physiology and productivity, drought stress is recognized as one of the most harmful factors. Drought stress induced crop yield loss is generally more significant then losses from other biotic and abiotic stresses, primarily because severity and duration of drought stress are critical (Eesha *et al*., 2024). The excessive formation of reactive oxygen species during drought stress results in oxidative damage and cell death (Kumar *et al*., 2024). During drought stress, disruptions in plant water relations lead to decreased water use efficiency. Citrus plants under drought conditions suffer significant losses in growth and cellular metabolic functions, resulting in reduced yield and fruit quality (Pérez-Pérez *et al*., 2008). Drought stress also causes declines in physiological parameters such as stomatal conductance, net CO_2 assimilation and leaf transpiration in citrus plants (Syvertsen and Garcia-Sanchez, 2014). As demonstrated by (García-Tejero *et al*., 2012) the fruit growth and flowering stages were the most sensitive periods in relation to irrigation water deficit and yield loss. Drought stress imposed a yield loss of up to 20% during the flowering stage whereas yield losses of nearly 10% and 6% were observed during the fruit growth or ripening stages respectively. Moreover under stress condition, significant loss in length, dry weight and fresh weight of both root and shoot accompanied with low germination percentage was recorded in Cleopatra sprouts (Zaher-Ara *et al*., 2016). The ability of citrus to withstand water deprivation varies by genotype, with the following order of drought resistance: *Citrus reticulata* > *Citrus* × *limonia* > *Citrus* × *limon* > *Poncirus trifoliate* > *Citrus chuana* > *Citrus* × *sinensis* > *Citrus verrucose* > *Citrus* × *paradisi.* (Rodríguez-Gamir *et al*., 2011; Zaher-Ara *et al*., 2016).

Water logging

The recent trends in climate change is responsible for increase in temperatures and altered water cycles, as evident by the increasing severity of droughts and aberrant precipitations consequently leading to waterlogging and flooding (Pérez-Jiménez and Pérez-Tornero, 2021). Flooding or waterlogging creates hypoxia, which triggers a wide spectrum of metabolic, biochemical, developmental and physiological changes in fruit trees (Habibi *et al*., 2023). This leads to the occurrence of desiccation symptoms; delayed root growth and transporter-driven ion uptake are also inhibited due to defective root respiration. Hypoxia is of special relevance to citrus plants due to lack of a specific adaptation *i.e.* aerenchyma formation or lenticel hypertrophy (Arbona and Gomez-Cadenas, 2008).

The major cause of waterlogging is the poor soil drainage system, excessive rainfall or irrigation and destruction of soil structure. The effects of flooding on plants mainly relate to the decline of energy shortage, therefore a reduced ion uptake and less energy for root growth (Rodríguez-Gamir *et al*., 2011). When plants are waterlogged, they cannot uptake water, leading to wilting of the foliage and shoots, a symptom that becomes more pronounced in warm weather. If root damage is extensive or soils remain waterlogged for prolonged periods, more severe symptoms can occur, including reduced chlorophyll levels, stunted growth and leaf senescence (Ashraf, 2012). However, the ability to endure waterlogging stress varies by genotype, with different citrus genotypes exhibiting a wide range of responses to waterlogging (Garcia-Sanchez *et al*., 2007). For instance, 'Cleopatra' is known to be very sensitive to flooding (Arbona and Gomez-Cadenas, 2008), whereas 'Forner Alcaide no. 5' has shown excellent tolerance to flooding conditions (Forner *et al*., 2003).

Cold stress

Exposure to low and very low temperatures is one of the most common environmental stresses affecting plants. In citrus, low temperatures can cause chilling and freezing injuries, thereby limiting crop production and yield (Zhang *et al*., 2011). Citrus fruits, especially at the ripening stage, can tolerate only 2-3 hours of temperatures dropping to -2 to -3°C; otherwise, the fruits decay. The ripening stage during January and February is the most vulnerable period for citrus crop yield (Zabihi *et al*., 2016). Citrus crops, which are among tropical and subtropical fruits, are generally classified as cold-tender plants, making them vulnerable to freezing stress (Fotouhi *et al*., 2008). Chilling results in the loss of membrane integrity and an increase in active oxygen radical production, leading to leaf damage and electrolyte leakage. The integrity of intracellular organelles is also disrupted, causing a loss of compartmentalization, impaired photosynthesis, reduced chlorophyll pigments, disrupted protein assembly and overall metabolic dysfunction (Mahajan and Tuteja, 2005). Young citrus shoots die at threshold temperature around -12°C, although some citrus fruits can tolerate temperatures as low as -10°C (Vu and Yelenosky, 1991). *Poncirus trifoliata* (L.) Raf. is noted as the most cold-tolerant citrus rootstock (Wang *et al*., 2015).

Above mentioned all the abiotic stresses lead to the production of reactive oxygen species (ROS) such as superoxide radicals, hydroxyl, hydrogen peroxide and singlet oxygen. ROS produced in chloroplasts and mitochondria during metabolic processes, can damage essential cellular components including proteins, membranes, pigments and nucleic acids (Rad *et al*., 2017). Moreover, significant increase in ROS accumulation and antioxidant enzyme activity has been reported in citrus plants under various abiotic stresses (Ziogas *et al*., 2021).

Tolerance mechanism towards abiotic stresses

Abiotic stresses, such as salinity, drought and temperature extremes, pose significant challenges to sustainable agricultural growth by impairing plant metabolic pathways. Salinity reduces photosynthetic efficiency and increases reactive oxygen and nitrogen species, prompting citrus plants to enhance antioxidant defenses (Hasanuzzaman *et al*., 2020; Ziogas *et al*., 2021). Na^+ transporters HKT1 and SOS1 help maintain ion balance under salt stress, with HKT1 preventing Na^+ overaccumulation in photosynthetic organs and SOS1 extruding Na^+ from root cells (Wang *et al*., 2014). In woody perennials like citrus,

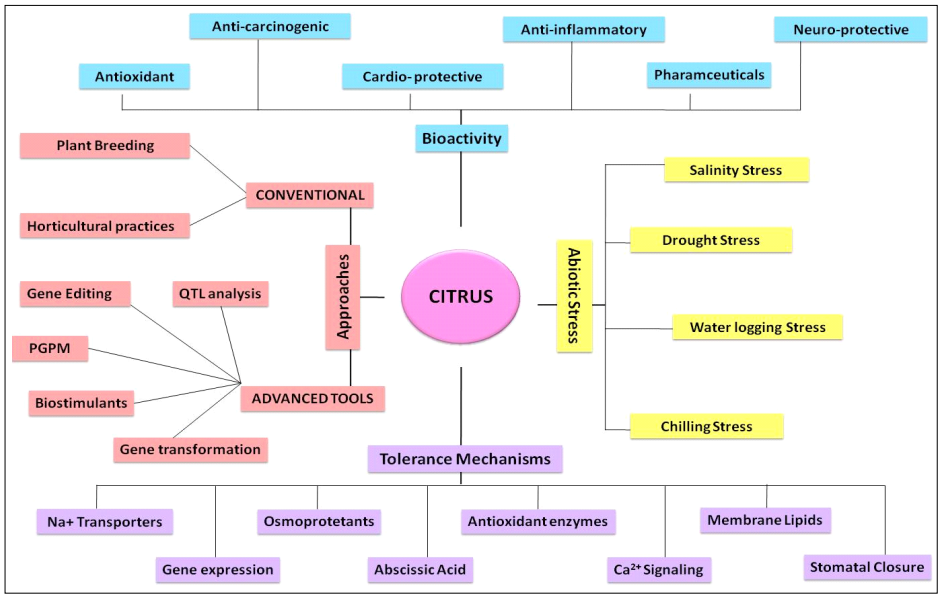


Fig 1: Aspects of abiotic stress management in citriculture.

excess Na^+ recovered by HKT1 may accumulate in woody tissues. The expression of SOS1 and HKT1 genes is linked to the ability of Cleopatra mandarin and trifoliate orange to exclude Na^+ (Martínez-Alcántara *et al*., 2015).

Under drought or high saline conditions, abscisic acid (ABA) acts as a crucial stress-signaling hormone (Bartels and Sunkar, 2005). It regulates stomatal closure, synthesis of compatible osmolytes and the upregulation of genes for adaptive responses. Increased ABA levels are linked to the upregulation of 9-cis-epoxycarotenoid dioxygenase (NCED), which converts 9-neoxanthin to xanthoxin, a key step in ABA biosynthesis. Moreover, active ABA can be removed by conjugation with hexoses via ABA O-glycosyl transferase (AOG), forming ABA-glycosyl ester (ABAGE) (Priest *et al*., 2006). Active ABA can be released from ABAGE degradation through the action of ABAGE β-glycosidase (BG18) (Schroeder and Nambara, 2006). Proline is synthesized from glutamate *via* glutamate semialdehyde and D1-pyrroline-5-carboxylate (P5C) through the actions of P5C synthetase (P5CS) and P5C reductase (P5CR). The genes encoding these enzymes are strongly upregulated under drought stress (Hare *et al*., 1999). Proline accumulation, triggered by free radicals from oxidative stress, protects plants during various environmental stresses. Proline levels are tightly regulated and only increase when synthesis outpaces degradation, as excessive proline is toxic to cells (Deuschle *et al*., 2001). Carbohydrates are also crucial for plant biomass, osmotic regulation and drought response. Progressive drought leads to a significant increase in soluble sugar content in some citrus crops, likely due to increased starch conversion into soluble sugars or decreased sugar utilization (Zaher-Ara *et al*., 2016). Drought stress typically enhances starch hydrolysis and reduces sucrose translocation, resulting in the accumulation of reducing sugars in leaf tissue, which provides osmotic protection (Campos *et al*., 1999; Zaher-Ara *et al*., 2016).

Waterlogging triggers hypoxia, leading to various physiological and molecular changes, including reduced photosynthetic activity and stomatal closure to increase water use efficiency (Martinez-Alcantara *et al*., 2012). A primary response to flooding is stomatal closure (Perez-Jimenez *et al*., 2017), which reduces gas exchange, lowers transpiration and increases water use efficiency to avoid dehydration. This response has been observed in previous citrus waterlogging studies (Li *et al*., 2006; Rodriguez-Gamir *et al*., 2011). Moreover, *Citrus* rootstocks' ability to regenerate roots has been found to influence their waterlogging tolerance (Pérez-Jiménez and Pérez-Tornero, 2021).

When plants detect stress, membrane destabilization occurs, which is the primary cause of plant damage from freezing (Steponkus and Webb, 1992). During acclimatization, the cryostability of the plasma membrane increases due to changes in lipid composition, enhancing resistance to dehydration. This involves an increased proportion of phospholipids, particularly di-unsaturated species of phosphatidylcholine and phosphatidylethanolamine and a reduced proportion of cerebroside lipids (Uemura *et al*., 1995). Calcium signaling involving specific kinases and transcription factors like HY5, plays a crucial role in cold response (Primo-Capella *et al*., 2021). The rise in calcium levels is transient, showing a characteristic peak facilitated by a specific vacuolar calcium antiporter, the calcium exchanger (CAX1 Ca^{2+}/H^+), which helps plants repeatedly respond to low-temperature signals. This calcium influx reaches receptor kinases regulated by calmodulin 1 and 2 (CRLK1 and CRLK2), initiating a signaling cascade specific to the cold response pathway (Yang *et al*., 2010). Plants process and integrate signals related to seasonal changes and light, which is crucial for acclimatization and cold tolerance. Hypocotyl 5 (HY5) transcription factor, a key modulator of light signaling and plant development, regulating other genes through various sub-networks (Catala *et al*., 2011). HY5 is overexpressed at low temperatures and induces genes responsive to cold stress by binding to the Z-box of promoters, part of the LTRE (low-temperature response element) domain. This light-mediated cold stress response is also present in citrus (Huang *et al*., 2019). In cold stress-tolerant plants, many genes involved in synthesizing osmoprotectants like proline, quaternary amines, sugars and sugar alcohols are highly expressed to combat stress adversities (Livingston and Henson, 1998). Proteins likely involved in stress tolerance include chaperones, late embryogenesis abundant (LEA) proteins, osmotin, antifreeze proteins, mRNA-binding proteins, key enzymes for osmolyte biosynthesis, fatty acid metabolism enzymes and lipid-transfer proteins (Holmberg and Bulow, 1998). Genes responsive to dehydration and cold stress encode various protective proteins, highlighting the need for multifaceted genetic approaches to enhance stress tolerance.

Strategies to combat abiotic stresses in citrus plants

Researchers have employed various strategies to enhance abiotic stress tolerance in crop plants ranging from traditional breeding methods to modern CRISPR/Cas9 technique (Ahmar *et al*., 2020; Zafar *et al*., 2020). Citriculture, in particular, faces significant challenges from drought and salinity, reducing citrus yield and fruit quality. Developing and disseminating strategies to help farmers adopt economically beneficial agricultural practices that minimize abiotic stress is crucial. Traditional breeding programs have produced improved citrus varieties, highlighting plant breeding as a key method for achieving stress adaptation (Govindaraj *et al*., 2015; Hasan *et al*., 2019). Research has shown that rootstocks are essential for a plant's ability to withstand water scarcity by influencing physiological performance through variations in leaf water potential, hydraulic conductance and stomatal conductivity (Rodriguez-Gamir *et al*., 2011). The genetic traits of the rootstock determine the scion's robustness and survival under water stress (Miles and Wayne, 2008). For instance,

orange trees (cv. Lane Late) grafted onto Cleopatra mandarin rootstock show higher water use efficiency and osmotic adjustment under drought conditions compared to those grafted onto Carrizo citrange hybrid rootstock (Garcia-Sanchez *et al*., 2007; Zaher-Ara *et al*., 2016). Additionally, horticultural practices such as using hydrogels, shading and treatments with persistent analogs of abscisic acid and polyamines have been successfully implemented to improve citrus performance under abiotic stress (Gimeno *et al*., 2014).

Genetic improvement for salinity tolerance in citrus species can be achieved through identifying natural variations via direct selection or quantitative trait loci (QTL) mapping. Due to limited success in direct selection under field conditions, breeders have focused on identifying transferable genes and gene products. Techniques like marker-assisted breeding and genetic transformation have gained prominence. QTL analysis involves crossing two parents with different quantitative traits to identify specific genes responsible for desired traits (Singh and Sharma, 2018). Notably, QTL mapping identified 70 potent QTLs in a BC1 population [*Citrus grandis* × (*Citrus grandis* × *Poncirus trifoliata*], with 69% related to salinity (Tozlu *et al*., 1999).

Salinity is more problematic on poorly drained clay or silt soils than on permeable sandy or gravelly soils. Citrus crops are commonly irrigated using drip or micro-sprinkler methods, ensuring water does not contact leaves to prevent salt burn. Salts can be leached from the root zone by applying large amounts of water to the soil once or twice a year (Simpson *et al*., 2014). Chemical priming is a promising method in plant stress physiology and crop management. Plants can develop “stress memory” after initial stress exposure, leading to better adaptation to subsequent stresses. Priming triggers responses to various stresses, offering low-cost protection under high-stress conditions (Colmenero-Flores *et al*., 2020). Exogenous application of nutrients and plant hormones has proven effective in making plants tolerant to flood stress. Scientists worldwide are researching this approach. For example, Ashraf *et al*. (2011) showed that exogenous potassium application, both in soil and as a foliar spray, alleviated waterlogging stress in cotton plants. Similarly, Yiu *et al*. (2009) found that exogenous application of spermidine and spermine led to biochemical and physiological adaptations in onions under flooding stress.

The use of biostimulants has become common among farmers for their protective effects against abiotic stress and positive contributions to overall plant growth (Van Oosten *et al*., 2017). Recent data show that bio stimulants aid in citrus root development and regulate osmoregulatory mechanisms in plant cells (Conesa *et al*., 2020). For example, orange trees (*Citrus sinensis* L.) sprayed with a commercial extract of *Ascophyllum nodosum* showed improved water relations and water use efficiency when irrigated with 50% of evapotranspired water (Spann and Little, 2011). The overuse of chemical fertilizers and pesticides has degraded soil quality, highlighting the need for sustainable agricultural techniques. Plant-growth-promoting microbes have emerged as a crucial strategy for enhancing plant growth and protection against abiotic stresses (Kumar *et al*., 2017). Arbuscular Mycorrhizal fungi, for instance, improve water deficit tolerance in the roots of Trifoliate orange by regulating polyamine homeostasis (Zou *et al*., 2021).

Traditional breeding methods for improving stress tolerance in crops have had limited success due to the complexity of these traits and low genetic variance under stress conditions. Advances in plant biotechnology over the past two decades have led to the identification and isolation of transcription factors related to cold stress tolerance. These include genes involved in the biosynthesis of Osmo protectants, membrane lipid modification, LEA proteins and detoxifying enzymes (Primo-Capella *et al*., 2021). The discovery of C-repeat binding factor (CBF) genes has been significant for low temperature adaptation and signal transduction (Forner-Giner *et al*., 2009). Overexpression of CBF4 in *Arabidopsis*, for instance, has enhanced tolerance to freezing and drought (Huang *et al*., 2015).

Minimizing the adverse effects of abiotic stresses requires precise and sophisticated agricultural practices that consider crop needs and resource availability. Manipulating specific plant genes to enhance production capacity and stress tolerance is becoming increasingly important. With climate threats affecting citrus crop production, advanced genomic and biotechnological techniques are essential for mitigating environmental impacts on citriculture.

CONCLUSION

Effective management of abiotic stress is crucial for achieving better yield and quality in agricultural crops. Although some citrus species have developed defense mechanisms against various stresses, most remain susceptible. Extensive research in genomics, proteomics and metabolomics, along with additional physiological approaches, is essential to understand the mechanistic roles of various factors in signal transduction pathways, their interactions and how they perceive and transmit signals to specific downstream responses under stress. Noteworthy stress management strategies proposed by researchers, combined with recent advancements in genetic engineering and biotechnological tools, offer new hope. Recent significant progress in understanding the complex mechanisms governing stress tolerance in citrus plants holds great potential for improving abiotic stress management in citriculture.

Conflict of interest

All authors declare that they have no conflict of interest.

REFERENCES

Ahmar, S., Gill, R.A., Jung, K.H., Faheem, A., Qasim, M.U., Mubeen, M. and Zhou, W. (2020). Conventional and molecular techniques from simple breeding to speed breeding in crop plants: Recent advances and future outlook. International Journal of Molecular Sciences. 21(7): 2590. doi: 10.3390/ijms21072590.

Alam, A., Ullah, H., Attia, A. and Datta, A. (2020). Effects of salinity stress on growth, mineral nutrient accumulation and biochemical parameters of seedlings of three citrus rootstocks. International Journal of Fruit Science. 20(4): 786-804.

Ali, S. and Moktan, M.W. (2014). Impact of farmers training on integarted pest management of mandarin oranges (*Citrus reticulata* Blanco.) in Darjeeling hills. Environment and Ecology. 32(2): 414-417.

Arbona, V. and Gomez-Cadenas, A. (2008). Hormonal modulation of citrus responses to flooding. Journal of Plant Growth Regulation. 27: 241-250.

Ashraf, M.A., Ahmad, M.S.A., Ashraf, M., Al-Qurainy, F. and Ashraf, M.Y. (2011). Alleviation of waterlogging stress in upland cotton (*Gossypium hirsutum* L.) by exogenous application of potassium in soil and as a foliar spray. Crop and Pasture Science. 62(1): 25-38.

Ashraf, M.A. (2012). Waterlogging stress in plants: A review. African Journal of Agricultural Research. 7(13): 1976-1981. doi: 10.5897/AJARX11.084.

Bartels, D. and Sunkar, R. (2005). Drought and salt tolerance in plants. CRC Critical Reviews in Plant Sciences. 24: 23-58.

Brumos, J., Talón, M., Bouhlal, R. and Colmenero Flores, J. (2010). Cl-homeostasis in includer and excluder citrus rootstocks: Transport mechanisms and identification of candidate genes. Plant, Cell and Environment. 33: 2012-2027.

Campos, P.S., Ramalho, J., Lauriano, J., Silva, M. and do Ceu Matos, M. (1999). Effects of drought on photosynthetic performance and water relations of four *Vigna* genotypes. Photosynthetica. 36: 79-87.

Catala, R., Medina, J. and Salinas, J. (2011). Integration of Low Temperature and Light Signaling during Cold Acclimation Response in *Arabidopsis*. Proceedings of the National Academy of Sciences of the United States of America. 108: 16475-16480.

Colmenero-Flores, J.M., Arbona, V., Morillon, R. and Gómez-Cadenas, A. (2020). Salinity and Water Deficit. In: The Genus *Citrus*; [Talon, M., Caruso, M., Gmitter, F.G. (Eds)]; Woodhead Publishing: Amsterdam, The Netherlands. pp. 291-309.

Conesa, M.R., Espinosa, P.J., Pallarés, D. and Pérez-Pastor, A. (2020). Influence of plant biostimulant as technique to harden citrus nursery plants before transplanting to the field. Sustainability. 12: 6190. https://doi.org/10.3390/su12156190.

De Storme, N. and Geelen, D. (2014). The impact of environmental stress on male reproductive development in plants: Biological processes and molecular mechanisms. Plant, Cell and Environment. 37: 1-18.

Deuschle, K., Funck, D., Hellmann, H., Däschner, K., Binder, S. and Frommer, W.B. (2001). A nuclear gene encoding mitochondrial D1-pyrroline-5-carboxylate dehydrogenase and its potential role in protection from proline toxicity. The Plant Journal. 27: 345-356.

Eesha, A., Kulshrestha, M., Choudhary, P., Kumar, A. and Nag, A.K. (2024). Metabolic and enzymatic evaluation of lentil (*Lens culinaris* M.) seedlings under drought stress. Indian Journal of Agricultural Research. 58(1): 43-48. doi: 10.18805/IJARe.A-5884.

Forner, J., Forner-Giner, M. and Alcaide, A. (2003). Forner-alcaide 5 and forner-alcaide 13: Two new citrus rootstocks released in Spain. Hort Science. 38: 629-630.

Forner-Giner, M.A.M. (2009). Performance of Forner-Alcaide 5 and Forner-Alcaide 13, hybrids of Cleopatra mandarin × Poncirus trifoliate, as salinity-tolerant citrus rootstocks. Journal of the American Pomological Society. 63: 72-80.

Fotouhi, G.R., Baghbanha, M.R., Hatamzadeh, A. and Heidari, M. (2008). Effect of water stress on freezing tolerance of mexican lime (*Citrus aurantifolia* L.) seedling. Horticulture Environment and Biotechnology. 49(5): 267-280.

García-Sánchez, F. and Syvertsen, J. (2006). Salinity tolerance of Cleopatra mandarin and Carrizo citrange citrus rootstock seedlings is affected by CO_2 enrichment during growth. Journal of the American Society for Horticultural Science. 131: 24-31.

Garcia-Sanchez, F., Syvertsen, J., Gimeno, V., Botia, P. and Perez-Perez, J. (2007). Responses to flooding and drought stress by two citrus rootstock seedlings with different water-use efficiency. Physiologia Plantarum. 130: 532-542.

García-Tejero, I., Durán-Zuazo, V.H., Arriaga-Sevilla, J. and Muriel-Fernández, J.L. (2012). Impact of water stress on citrus yield. Agronomy for Sustainable Development. 32: 651-659.

Gimeno, V., Díaz-López, L., Simón-Grao, S., Martínez, V., Martínez-Nicolás, J.J. and García-Sánchez, F. (2014). Foliar potassium nitrate application improves the tolerance of *Citrus macrophylla* L. seedlings to drought conditions. Plant Physiology and Biochemistry. 83: 308-315.

Govindaraj, M., Vetriventhan, M. and Srinivasan, M. (2015). Importance of genetic diversity assessment in crop plants and its recent advances: An overview of its analytical perspectives. Genetics Research International. 431487. doi: 10.1155/2015/431487.

Habibi, F., Liu, T., Shahid, M.A., Schaffer, B. and Sarkhosh, A. (2023). Physiological, biochemical and molecular responses of fruit trees to root zone hypoxia. Environmental and Experimental Botany. 206: 105179. https://doi.org/10.1016/j.envexpbot.2022.105179.

Hare, P., Cress, W. and Van Staden, J. (1999). Proline synthesis and degradation: A model system for elucidating stress-related signal transduction. Journal of Experimental Botany. 50: 413-434.

Hasan, N., Kamruzzaman, M., Islam, S., Hoque, H., Bhuiyan, F.H. and Prodhan, S.H. (2019). Development of partial abiotic stress tolerant *Citrus reticulata* Blanco and *Citrus sinensis* (L.) Osbeck through Agrobacterium-mediated transformation method. Journal of Genetic Engineering and Biotechnology. 17: 1-9.

Hasanuzzaman, M., Bhuyan, M., Zulfiqar, F., Raza, A., Mohsin, S.M., Mahmud, J.A., Fujita, M. and Fotopoulos, V. (2020). Reactive oxygen species and antioxidant defense in plants under abiotic stress: Revisiting the crucial role of a universal defense regulator. Antioxidants. 9: 681. https://doi.org/10.3390/antiox9080681.

He, D., Shan, Y., Wu, Y., Liu, G., Chen, B. and Yao, S. (2011). Simultaneous determination of flavanones, hydroxycinnamic acids and alkaloids in citrus fruits by HPLC-DAD-ESI/MS. Food Chemistry. 127: 880-885.

Hepaksoy, S. (2000). Effect of salinity on citrus. Journal of Aegean Agricultural Research. 2: 52-72.

Holmberg, N. and Bulow, L. (1998). Improving stress tolerance in plants by gene transfer. Trends in Plant Science. 3: 61-66.

Huang, D., Yuan, Y., Tang, Z., Huang, Y., Kang, C., Deng, X. and Xu, Q. (2019). Retrotransposon promoter of Ruby1 controls both light and cold-induced accumulation of anthocyanins in blood orange. Plant Cell and Environment. 42: 3092-3104.

Huang, X.S., Zhang, Q., Zhu, D., Fu, X., Wang, M., Zhang, Q., Moriguchi, T. and Liu, J.H. (2015). ICE1 of *Poncirus trifoliata* functions in cold tolerance by modulating polyamine levels through interacting with arginine decarboxylase. Journal of Experimental Botany. 66: 3259-3274.

Hussain, S., Luro, F., Costantino, G., Ollitrault, P. and Morillon, R. (2012). Physiological analysis of salt stress behaviour of citrus species and genera: Low chloride accumulation as an indicator of salt tolerance. South African Journal of Botany. 81: 103-112.

Kelebek, H. and Selli, S. (2011). Determination of volatile, phenolic, organic acid and sugar components in a Turkish cv. Dortyol [*Citrus sinensis* (L.) Osbeck] orange juice. Journal of the Science of Food and Agriculture. 91: 1855-1862.

Khoshbakht, D., Ramin, A.A. and Baninasab, B. (2015). Effects of sodium chloride stress on gas exchange, chlorophyll content and nutrient concentrations of nine citrus rootstocks. Photosynthetica. 53: 241-249.

Kumar, K.A., Kalarani, M.K., Vijayalakshmi, D., Geethalakshmi, V., Raveendran, M. and Anandhi, V. (2024). Evaluation of melatonin concentrations on germination and seedling traits of rice against drought stress. Indian Journal of Agricultural Research. 58(1): 29-35. doi: 10.18805/IJARe.A-6147.

Kumar, P., Rouphael, Y., Cardarelli, M. and Colla, G. (2017). Vegetable grafting as a tool to improve drought resistance and water use efficiency. Frontiers in Plant Science. 8: 1130. https://doi.org/10.3389/fpls.2017.01130.

Li, H., Syvertsen, J., McCoy, C., Stuart, R. and Schumann, A. (2006). Water stress and root injury from simulated flooding and *Diaprepes abbreviatus* root weevil larval feeding in citrus. Soil Science. 171: 138-151.

Liu, C.Y., Wang, P., Zhang, D.J., Zou, Y.N., Kuèa, K. and Wu, Q.S. (2018). Mycorrhiza-induced change in root hair growth is associated with IAA accumulation and expression of EXPs in trifoliate orange under two P levels. Scientia Horticulturae. 234: 227-235.

Livingston, D.P. and Henson, C.A. (1998). Apoplastic sugars, fructans, fructan exohydrolase and invertase in winter oat: Responses to second-phase cold hardening. Plant Physiology. 116: 403-408.

Lv, X., Zhao, S., Ning, Z., Zeng, H., Shu, Y., Tao, O., Xiao, C., Lu, C. and Liu, Y. (2015). Citrus fruits as a treasure trove of active natural metabolites that potentially provide benefits for human health. Chemistry Central Journal. 9: 68. doi: 10.1186/s13065-015-0145-9.

Mahajan, S. and Tuteja, N. (2005). Cold, salinity and drought stresses: An overview. Archives of Biochemistry and Biophysics. 444: 139-158.

Martinez-Alcantara, B., Jover, S., Quinones, A., Forner-Giner, M., Rodriguez-Gamir, J., Legaz, F. and Primo-Millo, E. (2012). Flooding affects uptake and distribution of carbon and nitrogen in citrus seedlings. Journal of Plant Physiology. 169: 1150-1157.

Martínez-Alcántara, B., Martínez-Cuenca, M.R., Quinones, A., Iglesias, D.J., Primo-Millo, E. and Forner-Giner, M.A. (2015). Comparative expression of candidate genes involved in sodium transport and compartmentation in citrus. Environmental and Experimental Botany. 111: 52-62.

Miles, C. and Wayne, M. (2008). Quantitative trait locus (QTL) analysis. Nature Education. 1(1): 208.

Mittler, R. (2002). Oxidative stress, antioxidants and stress tolerance. Trends in Plant Science. 7(9): 405-410.

Moya, J.L., Gomez-Cadenas, A., Primo-Millo, E. and Talon, M. (2003). Chloride absorption in salt-sensitive carrizo citrange and salt-tolerant Cleopatra mandarin citrus rootstocks is linked to water use. Journal of Experimental Botany. 54: 825-833.

Nayem, S.A., Salahuddin, M., Chowdhury, M., Sultana, N., Masum, G.Z.H., Rahman, M.S. and Jamal, M.A.H.M. (2020). Combined effect of salt stress and *Xanthomonas axonopodis* pv citri on citrus (*Citrus aurantifolia*). Heliyon. 6: e03403. doi: 10.1016/j.heliyon.2020.e03403.

Osakabe, Y., Osakabe, K. and Shinozaki, K. (2013). Plant environmental stress responses for survival and biomass enhancement. Climate Change and Plant Abiotic Stress Tolerance. 4: 81-107.

Patra, B., Tudu, B., Ali, S. and Samanta, A. (2017). An Insight into bio-ecology and management strategies of citrus leaf miner (*Phyllocnistis citrella* Stainton, Lepidptera: Gracillariidae), a potentially serious pest of Darjeeling mandarin. International Journal of Basic and Applied Biology. 4(2): 98-101.

Pereira, G.M. and Scherer, S.J. (Eds.) (2023). Citrus Research-horticultural and Human Health Aspects. Intech Open. doi: 10.5772/intechopen.100891.

Perez-Jimenez, M., Hernandez-Munuera, M., Zapata, M., Lopez-Ortega, G. and del Amor, F. (2017). Two minuses can make a plus: Waterlogging and elevated CO_2 interactions in sweet cherry (*Prunus avium*) cultivars. Physiologia Plantarum. 161: 257-272.

Pérez-Jiménez, M. and Pérez-Tornero, O. (2021). Short-term waterlogging in citrus rootstocks. Plants. 10: 2772. https://doi.org/10.3390/plants10122772.

Pérez-Pérez, J.G., Romero, P., Navarro, J.M. and Botía, P. (2008). Response of sweet orange cv 'Lane late' to deficit irrigation in two rootstocks. I: Water relations, leaf gas exchange and vegetative growth. Irrigation Science. 26: 415-425.

Priest, D.M., Ambrose, S.J., Vaistij, F.E., Elias, L., Higgins, G.S., Ross, A.R.S., Abrams, S.R. and Bowles, D.J. (2006). Use of the glucosyltransferase UGT71B6 to disturb abscisic acid homeostasis in *Arabidopsis thaliana*. Plant Journal. 46: 492-502.

Primo-Capella, A., Martínez-Cuenca, M.-R. and Forner-Giner, M.Á. (2021). Cold stress in citrus: A molecular, physiological and biochemical perspective. Horticulturae. 7: 340. https://doi.org/10.3390/horticulturae7100340.

Prior, L.D., Grieve, A.M., Bevington, K.B. and Slavich, P.G. (2007). Long-term effects of saline irrigation water on 'Valencia' orange trees: Relationships between growth and yield and salt levels in soil and leaves. Australian Journal of Agricultural Research. 58: 349-358. doi: 10.1071/AR06199.

Rad, R., Dordipour, Z.E. and Tajvar, Y. (2017). Evaluation of low temperature tolerance indices in seedling of *Citrus aurantium* under potassium nitrate nutrition. Iranian Journal of Plant Physiology. 7(2): 2007-2015.

Rodríguez-Gamir, J., Ancillo, G., Aparicio, F., Bordas, M., Primo-Millo, E. and Forner-Giner, M.Á. (2011). Water-deficit tolerance in citrus is mediated by the down regulation of PIP gene expression in the roots. Plant and Soil. 347: 91-104.

Rodriguez-Gamir, J., Ancillo, G., Gonzalez-Mas, M., Primo-Millo, E. and Forner-Giner, M. (2011). Root signalling and modulation of stomatal closure in flooded citrus seedlings. Plant Physiology and Biochemistry. 49: 636-645.

Sah, S.K., Reddy, K.R. and Li, J. (2016). Abscisic acid and abiotic stress tolerance in crop plants. Frontiers in Plant Science. 7: 571. https://doi.org/10.3389/fpls.2016.00571.

Santana-Vieira, D.D.S., Freschi, L., da Hora Almeida, L.A., de Moraes, D.H.S., Neves, D.M., Dos Santos, L.M., Bertolde, F.Z., Soares Filho, W.S., Coelho Filho, M.A. and da Silva Gesteira, A. (2016). Survival strategies of citrus rootstocks subjected to drought. Scientific Reports. 6: 1-12.

Schroeder, J.I. and Nambara, E. (2006). A quick release mechanism for abscisic acid. Cell. 126: 1023-1025.

Sharma, K.K. and Sachan, H.K. (2024). Salinity and variety effects on yield, yield attributes and soil of tomato under greenhouse conditions of Central Fiji. Indian Journal of Agricultural Research. 58(2): 295-300. doi: 10.18805/IJARe.AF-800.

Simpson, C.R., Nelson, S.D., Melgar, J.C., Jifon, J., King, S.R., Schuster, G. and Volder, A. (2014). Growth response of grafted and ungrafted citrus trees to saline irrigation. Scientia Horticulturae. 169: 199-205.

Singh, A. and Sharma, P. (2018). Recent insights into physiological and molecular regulation of salt stress in fruit crops. Advances in Plants and Agriculture Research. 8: 171-183.

Sinky, Sapna, Sarita, Meenakshi, Kumar, V., Soni, A. and Sharma, K.D. (2024). Impact of silicon application on physiochemical traits of *Vigna radiata* exposed to salinity stress. Indian Journal of Agricultural Research. 58(1): 113-119. doi: 10.18805/IJARe.A-6150.

Spann, T.M. and Little, H.A. (2011). Applications of a commercial extract of the brown seaweed *Ascophyllum nodosum* increases drought tolerance in container-grown 'Hamlin' sweet orange nursery trees. Hort Science. 46: 577-582.

Steponkus, P.L. and Webb, M.S. (1992). Freeze-induced Dehydration and Membrane Destabilization in Plants. In: Water and Life Springer, Berlin/Heidelberg, [Somero, G.N., Osmond, C.B. and Bolis, C.L. (Eds.)]. Germany. pp. 338-362.

Syvertsen, J.P. and Hanlin, E.A. (2008). Citrus tree stresses: Effects on growth and yield. Document HS1138. University of Florida, Granville, FL. 12 pp.

Syvertsen, J.P. and Garcia-Sanchez, F. (2014). Multiple abiotic stresses occurring with salinity stress in citrus. Environmental and Experimental Botany. 103: 128-137.

Tozlu, I., Guy, C.L. and Moore, G.A. (1999). QTL analysis of Na^+ and Cl^- accumulation related traits in an intergeneric BC1 progeny of *Citrus* and *Poncirus* under saline and nonsaline environments. Genome. 42: 692-705.

Uemura, M., Joseph, R.A. and Steponkus, P.L. (1995). Cold acclimation of *Arabidopsis thaliana* (Effect on plasma membrane lipid composition and freeze-induced lesions). Plant Physiology. 109: 15-30.

Van Oosten, M.J., Pepe, O., De Pascale, S., Silletti, S. and Maggio, A. (2017). The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. Chemical and Biological Technologies in Agriculture. 4: 5. https://doi.org/10.1186/s40538-017-0089-5.

Vu, J.C.V. and Yelenosky, G. (1991). Photosynthetic responses of citrus trees to soil flooding. Physiologia Plantarum. 81: 7-14.

Wang, M., Zhang, X. and Liu, J.-H. (2015). Deep sequencing-based characterization of transcriptome of trifoliate orange [*Poncirus trifoliata* (L.) Raf.] in response to cold stress. BMC Genomics. 16: 555. https://doi.org/10.1186/s12864-015-1629-7.

Wang, Q., Guan, C. and Wang, S.M. (2014). Coordination of AtHKT1; 1 and AtSOS1 facilitates Na^+ and K^+ homeostasis in *Arabidopsis thaliana* under salt stress. Journal of Plant Biology. 57: 282-290.

Wu, Q.S., Zou, Y.N. and Huang, Y.M. (2013). The arbuscular mycorrhizal fungus *Diversispora spurca* ameliorates effects of waterlogging on growth, root system architecture and antioxidant enzyme activities of citrus seedlings. Fungal Ecology. 6: 37-43.

Yang, T., Chaudhuri, S., Yang, L., Du, L. and Poovaiah, B.W. (2010). A calcium/calmodulin-regulated member of the receptor-like kinase family confers cold tolerance in plants. Journal of Biological Chemistry. 285: 7119-7126.

Yiu, J.C., Liu, C.W., Fang, D.Y.T. and Lai, Y.S. (2009). Waterlogging tolerance of Welsh onion (*Allium fistulosum* L.) enhanced by exogenous spermidine and spermine. Plant Physiology and Biochemistry. 47: 710-716.

Zabihi, H., Vogeler, I., Amina, Z.M. and Gourabi, B.R. (2016). Mapping the sensitivity of citrus crops to freeze stress using a geographical information system in Ramsar, Iran. Weather and Climate Extremes. 14: 17-23.

Zafar, S.A., Zaidi, S.S., Gaba, Y., Singla-Pareek, S.L., Dhankher, O.P., Li, X., Mansoor, S. and Pareek, A. (2020). Engineering Abiotic Stress Tolerance *via* CRISPR/Cas-mediated Genome editing. Journal of Experimental Botany. 71(2): 470-479.

Zaher-Ara, T., Boroomand, N. and Sadat-Hosseini, M. (2016). Physiological and morphological response to drought stress in seedlings of ten citrus. Trees. 30: 985-993.

Zhang, C., Meng, S. and Li, M. (2016). Genomic identification and expression analysis of the phosphate transporter gene family in poplar. Frontiers in Plant Science. 7: 1398. https://doi.org/10.3389/fpls.2016.01398.

Zhang, Q., Zhang, J.Z., Chow, W.S., Sun, L.L., Chen, J.W., Chen, Y.J. and Peng, C.L. (2011). The influence of low temperature on photosynthesis and antioxidant enzymes in sensitive banana and tolerant plantain (*Musa* sp.) cultivars. Photosynthetica. 49: 201-208.

Ziogas, V., Tanou, G., Morianou, G. and Kourgialas, N. (2021). Drought and salinity in citriculture: Optimal practices to alleviate salinity and water stress. Agronomy. 11: 1283. https://doi.org/10.3390/agronomy11071283.

Zhu, X.C., Song, F.B., Liu, S.Q. and Liu, T.D. (2011). Effects of arbuscular mycorrhizal fungus on photosynthesis and water status of maize under high temperature stress. Plant and Soil. 346: 189-199.

Zhu, J.K. (2016). Abiotic stress signaling and responses in plants. Cell. 167: 313-324.

Zou, Y.N., Wang, P., Liu, C.Y., Ni, Q.D., Zhang, D.J. and Wu, Q.S. (2017). Mycorrhizal trifoliate orange has greater root adaptation of morphology and phytohormones in response to drought stress. Scientific Reports. 7: 41134. https://doi.org/10.1038/srep41134.

Zou, Y., Zhang, F., Srivastava, A.K., Wu, Q. and Kuca, K. (2021). Arbuscular mycorrhizal fungi regulate polyamine homeostasis in roots of trifoliate orange for improved adaptation to soil moisture deficit stress. Frontiers in Plant Science. 11: 600792. https://doi.org/10.3389/fpls.2020.600792.