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Harnessing boron application for environmental stress alleviation in fruit crops: Enhancing horticultural sustainability in the view of climate change

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Abstract
To ensure food security and environmental preservation, sustainable horticultural methods are becoming more important as climate change presents unmatched challenges to agricultural systems globally. Climate change induced environmental stresses significantly affects the fruit crops, which are vital to global agriculture and human nutrition. In this regard, boron a vital micronutrient emerges as a potentially useful instrument for reducing environmental stress and boosting the resilience of fruit crops. This review paper, written in the context of horticulture sustainability and climate change adaptation, critically investigates the impact of boron application in damping environmental stress in fruit crops. We investigate the physiological processes by which boron affects how plants react to abiotic stresses like salinity, drought, and severe temperatures. Additionally, we evaluate how boron affects fruit quality features in the context of shifting environmental variables, such as yield, nutritional value, and postharvest characteristics. We also go over agronomic techniques and application strategies for maximizing boron usage in fruit crop production systems, taking into account both traditional and novel ways. In addition, an assessment is conducted on the ecological consequences and any hazards linked to the application of boron to guarantee sustainable management approaches. In summary, this research highlights the need to incorporate boron-based tactics into horticultural operations to improve fruit crop resilience to climate change, thus supporting global food security and agricultural sustainability.

Keywords: Harnessing boron, environmental stress alleviation, fruit crops, sustainability, climate change

1. Introduction

Sustainability is the ability to fulfill present demands without sacrificing the potential of future generations for satisfying their own requirements while preserving biodiversity and ecological processes. Research shows the significance of utilizing multi-criteria sustainability evaluations, like the ELECTRE IV approach, which ranks crops according to environmental, energy and technological variables (Banaeian *et al.*, 2022) [3]. Furthermore, sustainable horticultural methods depend heavily on the management of water resources, with a focus on integrated water management that takes social, environmental and technological factors into consideration (Hassan *et al.,* 2022) [33]. In addition, the production of waste from horticulture and its potential for recycling into valuable goods emphasize the necessity of sustainable extraction and usage techniques in order to lower pollution levels and maintain a green environment (El-Gayar, 2021) [25]. In general, eco-friendly cultivation methods, waste minimization and effective resource management are all the components of sustainable horticulture crop production that support long-term environmental growth. Global agriculture faces a variety of challenges as a result of climate change, including major effects on fruit crop production systems, threats to food security, and disruptions to rural lives. The main effects of climate change on agricultural ecosystems include rise in temperature, changed precipitation patterns, extreme weather events and altered dynamics of pests and diseases (Lobell *et al.*, 2011; Change, 2019) [45]. Agroecosystem's delicate equilibrium is upset by these changes, which lower agricultural yields, degrade crop quality and make crops more vulnerable to biotic and abiotic stresses.

Fruit crops are especially susceptible to the effects of climate change because of their lengthy production cycles and sensitivity to climatic variables (Hatfield *et al.*, 2011 [36];

Wheeler *et al.*, 2013) [73]. Increased temperatures have the potential to impact yield and quality characteristics by quickening the ripening process of fruit, hindering the growth of flowers and changing the composition of fruit (Luedeling *et al.*, 2011; Challinor *et al.*, 2014) [17, 46]. Furthermore, the production of fruit crops is immediately threatened by extreme weather events such as heatwaves, droughts, floods and storms, which can result in yield losses, physical damage to crops and supply chain disruption (Porter *et al.*, 2014; Battisti and Naylor, 2009) [6, 58]. Further complicated fruit crop management had changed pest and disease dynamics brought on by shifting climatic circumstances, which lead to an increase in pest pressure, an extension of pest ranges and the appearance of new pathogens (Bebber *et al.*, 2013; Chakraborty *et al.*, 2018) [7, 16]. Considering these difficulties, swift action is needed to increase the ability of fruit crop production systems to withstand the effects of climate change by implementing cutting-edge technologies, sustainable farming methods and successful mitigation and adaptation plans (Rosenzweig *et al.*, 2014; Thornton *et al.*, 2014) [62, 69]. A viable strategy for reducing environmental stress and boosting fruit crop's tolerance to climate change is to make use of micronutrients like boron. Water stress in fruit crops is made worse by variations in precipitation patterns, such as variations in the frequency and intensity of rainfall. This results in decreased water availability, poor nutrient uptake and weakened physiological processes (Rodríguez *et al.*, 2011; Greer *et al.*, 2012) [33, 61].

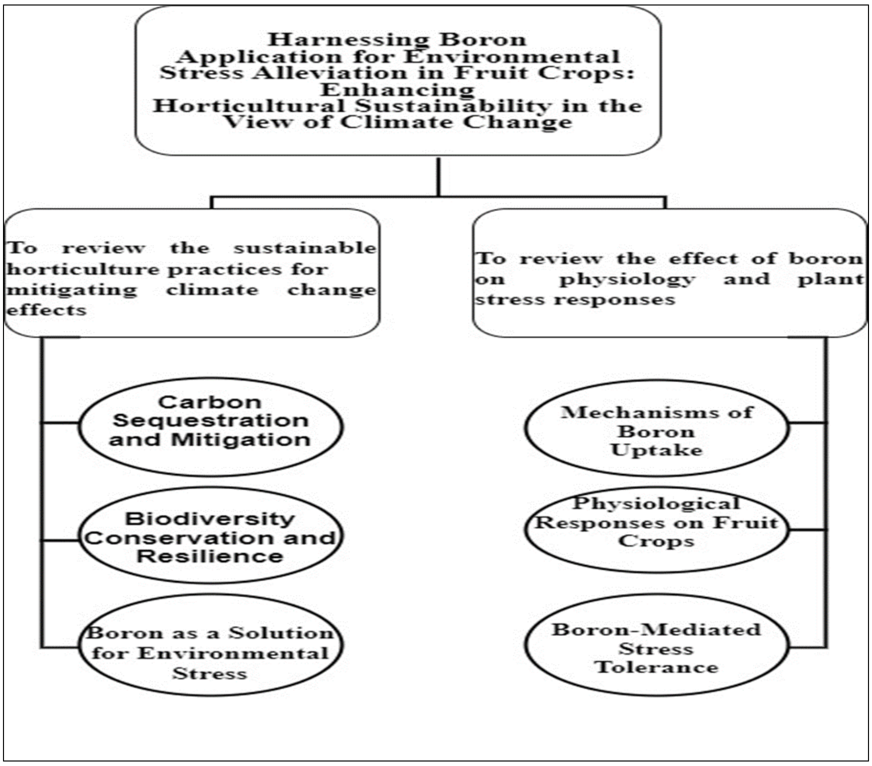

Fig 1: Conceptual Framework on Boron Application for Environmental Stress Alleviation

This paper delves deeply into the environmental preservation, sustainable horticultural methods for Environmental Stress Alleviation in Fruit Crops: Enhancing Horticultural Sustainability in the View of Climate Change. The objective is to carefully examine the beneficial impacts they have made in these areas, investigate the possible risks they may create, and identify the weaknesses that could undermine their reliability. To achieve this, our study will conduct a intuitive review of literature from research as well as review papers. The content in the whole literature are mostly text documents which is review centered on Harnessing Boron Application for Environmental Stress Alleviation.

Sustainable Horticulture Practices in Mitigating Climate Change Effects

The use of sustainable horticultural methods is crucial in reducing the detrimental impacts of climate change on agricultural systems and enhancing the resilience of food supply. Farmers can reduce greenhouse gas emissions, preserve natural resources, improve ecosystem services and adjust to shifting environmental conditions by implementing sustainable horticultural practices. By lowering atmospheric CO_2 levels, sustainable horticultural practices like agroforestry, cover crops and reduced tillage can mitigate climate change by sequestering carbon in soils and biomass (Change, 2007; Lal, 2018) [43]. These methods lower the carbon footprint of agricultural operations while increasing the amount of organic matter in the soil and enhancing its fertility and structure. Drip irrigation, rainwater harvesting and soil moisture monitoring are examples of sustainable water management strategies that help maximize water usage efficiency in horticulture systems, particularly in water-stressed areas (Pereira *et al.*, 2012; Teston *et al.*, 2022) [56, 68]. These techniques lessen the negative effects of drought and water scarcity brought on by climate change on crop resilience and productivity by preserving water resources and lowering the need for irrigation. By preserving native flora and fauna, using polyculture and agroecological principles and creating habitat corridors and green spaces, sustainable horticulture supports biodiversity conservation (Buchholz and Egerer, 2020; Garibaldi *et al.*,

2017) [14, 29]. Diverse cropping systems provide pollination services, disease and pest control and ecosystem resilience, all of which support the long-term sustainability of agricultural landscapes. Organic farming, precision agriculture and integrated pest management (IPM) are examples of sustainable intensification techniques that minimize environmental degradation, boost agroecosystem resilience and lessen dependency on synthetic inputs (Pretty *et al.*, 2018; Ponisio *et al.*, 2015) [57, 59]. These methods strengthen soil health, lower greenhouse gas emissions and support climate-smart agricultural systems that can adjust to shifting weather patterns. To create robust cultivars that are resistant to pests, diseases and climatic challenges, sustainable horticulture places a strong emphasis on the preservation and application of genetic variety in crop breeding programs (Dwivedi *et al.*, 2016; Tester and Langridge, 2010) [24, 67]. A more resilient agricultural system can be achieved through sustainable horticulture, which promotes participatory plant breeding programs and diversifies crop genetic resources. Finally, it should be noted that sustainable horticultural techniques have several advantages for improving ecosystem resilience, reducing the effects of climate change on agricultural systems, and advancing long-term food security and environmental sustainability.

Boron as a Potential Solution for Environmental Stress

Fruit crops are important part of the world's agricultural system since they give millions of people their economic livelihoods and crucial nutrients. However, climate change-induced environmental stresses such as drought, salinity and temperature extremes are posing an increasing danger to the sustainability and productivity of fruit crop production (Lobell *et al.*, 2011; Change, 2019) [45]. In this context, one important element that shows promise for reducing environmental stress and strengthening fruit crop's resistance to unfavorable growth conditions is boron. In several physiological processes necessary for plant growth, development and stress tolerance, boron is an essential component (Blevins and Lukaszewski, 1998; Wimmer and Eichert, 2013) [11, 74]. Boron affects how plants react to abiotic stressors by sustaining cell integrity, osmotic balance and water relations. It is a cofactor for several enzymes involved in cell wall formation, glucose metabolism and hormone control (Marschner *et al.*, 2011) [49]. Additionally, boron helps in controlling transpiration rates, photosynthetic efficiency and stomatal conductance, which improves plant drought tolerance and water use efficiency (Goldbach and Wimmer, 2007) [31, 74]. Apart from its physiological functions, boron enhances nutrient uptake, transport and utilization in plants by interacting with other vital elements, such as calcium, magnesium and potassium (Camacho-Cristóbal *et al.*, 2015; Shorrocks, 1997) [15, 65]. Fruit crop performance under challenging growth conditions is improved by the synergistic interaction of boron and other nutrients, which increases plant tolerance to nutrient imbalances and environmental stresses (Hu and Brown, 1994; Wimmer and Eichert, 2013) [13, 38, 74]. Recent studies have shown how boron can reduce environmental stress and improve the quality and production of fruit crops grown in difficult environments. According to studies (Bashan *et al.*, 2014) [5], boron supplementation can improve water and nutrient uptake, enhance antioxidant defence mechanisms and reduce oxidative damage to plant tissues, all of which can negatively affect fruit crops. Further evidence that boron application can increase fruit crop marketability and farmer's financial returns comes from studies showing a substantial increase in fruit yield, size, colour, flavor and nutritional composition (Bangerth, 1979; Marschner *et al.*, 2011) [4, 49]. Growers can leverage the benefits of boron supplementation to increase fruit crop resilience, sustainability and profitability in the face of environmental stressors brought on by climate change by improving boron fertilization processes and application techniques. Boron is a promising way to reduce environmental stress and increase fruit crop's ability to withstand the effects of climate change. In the era of climate change, farmers may harness the potential of boron supplementation to sustainably improve fruit crop production, quality and profitability by understanding the physiological mechanisms underpinning boron's impacts and putting suitable agronomic methods into practice.

Boron Physiology and Role in Plant Stress Responses

For plants to grow, develop and be able to withstand stress, boron is a micronutrient that is necessary for several physiological processes. According to (Brown *et al.*, 2002) [13], boron is necessary for the synthesis and cross-linking of pectic polysaccharides in plant cell walls, which are vital for preserving the integrity, strength and structure of cell walls. The cell wall matrix is stabilized by boron bridges between rhamnogalacturonan II (RG-II) molecules, which enables the cell wall matrix to tolerate mechanical stress and turgor pressure (Kobayashi *et al.*, 1996) [39]. By controlling the activity of membrane-bound enzymes and transport proteins involved in ion homeostasis, nutrient absorption and signalling pathways, boron affects membrane function and permeability (Wimmer and Eichert, 2013) [74]. By modifying the function of plasma membrane proteins including proton pumps and aquaporins, boron helps to maintain the osmotic equilibrium inside cells (Miwa and Fujiwara, 2010) [52]. By affecting the activity of enzymes involved in sugar synthesis, transport and utilization, such as sucrose synthase and invertase, boron contributes to the metabolism of carbohydrates (Bellaloui *et al.*, 2009; Blevins and Lukaszewski, 1998) [9, 11]. Furthermore, boron regulates the production, transport and signalling processes of plant hormones including auxin and ethylene through interactions with these hormones (Camacho-Cristóbal *et al.*, 2015; Schnurbusch *et al.*, 2010) [15, 64].

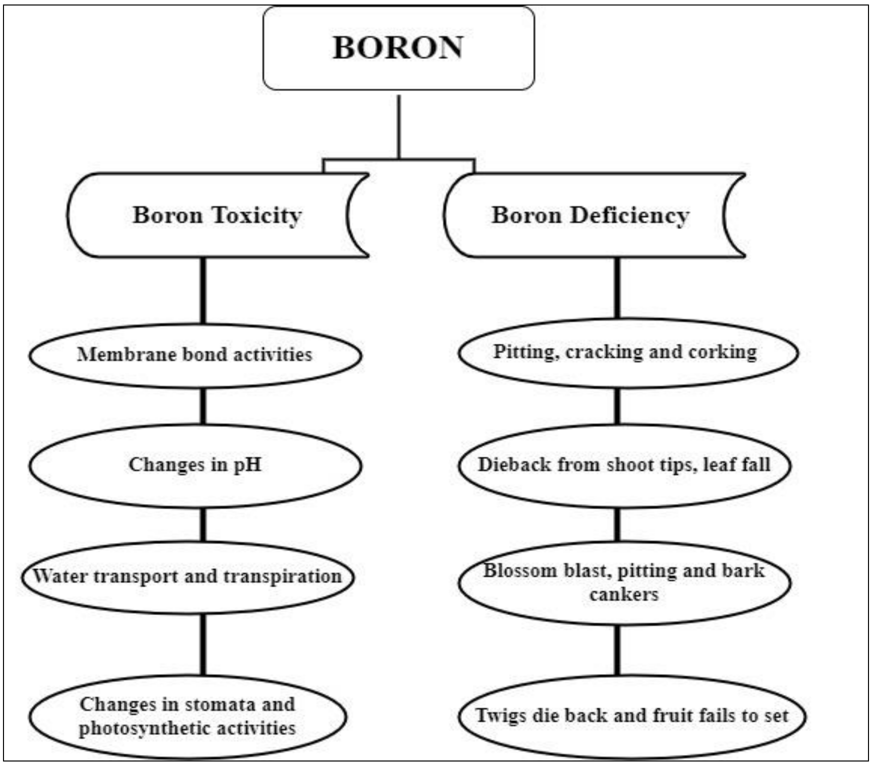

Fig 2: Boron Physiology and Role in Plant Stress Responses

Throughout the processes of pollen germination, tube expansion and fertilization, boron is very important for reproductive development (Brown *et al.*, 2002) [13]. Insufficient amounts of boron cause aberrant formation of pollen, decreased viability of pollen and poor fertilization, which in turn causes poor fruit set and yield losses in a variety of crop species (Goldbach and Wimmer, 2007) [31, 74]. By interacting with other necessary minerals, such as calcium, magnesium and potassium, and modifying their uptake kinetics and translocation processes, boron affects the uptake and transport of nutrients in plants (Camacho-Cristóbal *et al.*, 2015; Wimmer and Eichert, 2013) [15, 74]. A lack of boron damages nutritional balance and hinders the uptake of other minerals, causing nutrient imbalances and physiological problems in plants (Shorrocks, 1997; Bellaloui *et al.*, 2010) [10, 65]. The vital roles that boron plays in the growth and development of plants are crucial to several physiological processes that are required for plant health, yield and resilience to stress in agricultural environments.

Mechanisms of Boron Uptake, Transport and Distribution within Plants

Complex processes involved in boron uptake, transport and distribution within plants make sure that different tissues and organs receive the right amount of boron while preserving cellular homeostasis. Boron uptake by plant roots occurs predominantly as boric acid ($B(OH)_3$), a neutral molecule that is highly soluble in water and present in the soil solution (Camacho-Cristóbal *et al.*, 2015; Dannel *et al.*, 2002) [15, 22]. The concentration difference between the soil solution and the cytoplasm of the root cell drives passive diffusion across the plasma membrane, which facilitates the uptake of boron by the roots (Dannel *et al.*, 2002; Miwa and Fujiwara, 2010) [22, 52]. Following uptake by the roots, boron is mostly carried via undissociated boric acid molecules ($B(OH)_3$) through the xylem of the plant, with a small amount of borate ions ($B(OH)^{-4}$) in an alkaline environment (Camacho-Cristóbal *et al.*, 2015; Marschner, 2012) [15, 48]. Root-to-shoot partitioning, hydraulic conductivity and boron concentration gradients are some of the variables that affect boron transport in the xylem, which is propelled by transpiration-induced water flow (Shorrocks, 1997; Wimmer and Eichert, 2013) [65, 74]. Boron performs vital functions in cell division, expansion and reproductive development in actively growing tissues and organs of the plant, such as meristematic areas, young leaves, flowers and developing fruits (Brown *et al.*, 2002; Marschner, 2012) [13, 48]. Numerous physiological processes, such as phloem loading and unloading, cell compartmentalization and redistribution between tissues via symplastic and apoplastic pathways, control the distribution of boron (Shorrocks, 1997; Wimmer and Eichert, 2013) [65, 74]. To avoid deficiencies or toxicity symptoms and to sustain the best possible growth and development, plant tissue's balance of boron is strictly controlled (Camacho-Cristóbal *et al.*, 2015; Miwa and Fujiwara, 2010) [15, 52]. Sophisticated regulatory processes including boron transporters, membrane proteins and signalling pathways that sense and respond to changes in boron availability and demand govern boron uptake, transport and distribution (Camacho-Cristóbal *et al.*, 2015; Miwa and Fujiwara, 2010) [15, 52]. The methods of boron uptake, transport and distribution in plants are highly regulated, ensuring that this crucial element is well utilized for plant growth, development and physiological functions.

Table.1: Harnessing Boron Application for Environmental Stress Alleviation in Fruit Crops

Sr. No.	Terminologies	Citation
1	Boron physiology and role in plant stress responses	Herrera-Rodríguez *et al.*, (2010) [37]
		Vera-Maldonado *et al.*, (2024) [71]
		Brown *et al.*, (2002) [13]
		Garcia-Sanchez *et al.*, (2020)
		Pandey *et al.*, (2019) [54]
2	Physiological responses of fruit crops to environmental stress	Madani *et al.*, (2019) [47]
		Kondle *et al.*, (2023) [40]
		Rao *et al.*, (2016) [60]
		Flore *et al.*, (1989 [27]
		Goswami *et al.*, (2022) [32]
3	Boron-Mediated stress tolerance in fruit crops	Michailidis *et al.*, (2023) [50]
		Behera *et al.*, (2023) [8]
		Cheng *et al.*, (2023) [21]
		Chen *et al.*, (2022) [20]
4	Influence of boron on fruit quality attributes	Swathi *et al.*, (2019) [66]
		Gulut *et al.*, (2021)
		Kumar *et al.*, (2017) [41]
		Vishekaii *et al.*, (2019) [72]
		Ahmad *et al.*, (2018) [1]

Physiological Responses of Fruit Crops to Environmental Stress

In response to environmental stressors such as heat, salt, drought and nutrient shortages, fruit crops display a range of physiological reactions that can hurt plant growth, development and productivity. By regulating physiological processes and strengthening stress tolerance mechanisms, boron, an important micronutrient, helps fruit crops withstand the negative effects of stress. Osmotic stress and water deficit situations are caused by environmental stresses such as salinity and drought, which interfere with fruit crop's ability to absorb water and transpire (Munns and Tester, 2008) [53, 67]. By controlling stomatal conductance, transpiration rates and osmotic adjustment processes, boron improves fruit crop resistance to water stress while preserving cellular water balance and turgor pressure (Goldbach and Wimmer, 2007; Shorrocks, 1997) [31, 65, 74]. In fruit crops, photosynthetic activity and carbon absorption processes are hampered by environmental stressors such as heat and nutrient shortages. This reduces biomass accumulation and yield losses (Flexas *et al.*, 2004) [26]. By increasing electron transport rates, Rubisco enzyme activity and chlorophyll synthesis, boron supplementation increases the photosynthetic efficiency of fruit crops and reduces the detrimental effects of stress on carbon fixation and assimilation (Wimmer and Eichert, 2013; Brown *et al.*, 2002) [13, 74].

Reactive oxygen species (ROS) are produced in fruit crops as a result of environmental stresses like heat, salt and oxidative stress. This results in cellular damage and oxidative stress (Gill and Tuteja, 2010; Mittler, 2002) [30, 50]. By boosting the activity of antioxidant enzymes like peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD), as well as by directly scavenging reactive oxygen species (ROS), boron improves the antioxidant defence mechanisms of fruit crops. This reduces oxidative damage and increases stress tolerance (Wimmer and Eichert, 2013) [74]. Fruit crops experience growth, development and stress responses when exposed to environmental stresses including heat and drought, which upset hormonal balance and signalling pathways (Peleg and Blumwald, 2011; Yang *et al.*, 2006) [55, 75]. By influencing the biosynthesis, transport and signalling processes of plant hormones like auxin and ethylene as well as the expression of genes that respond to stress, boron enhances the ability of fruit crops to withstand environmental stress (Camacho-Cristóbal *et al.*, 2015; Schnurbusch *et al.*, 2010) [15, 64]. Reproductive development and fruit set in fruit crops are hampered by environmental stressors such as heat and water stress, which lowers fruit yield and quality (Saini and Lalonde, 1997; Zinn *et al.*, 2010) [63, 76]. By improving pollen germination, tube growth and fertilization processes as well as flower and fruit development, Boron supplementation enhances fruit crop reproductive development and reduces the detrimental effects of stress on fruit yield and marketability (Brown *et al.*, 2002) [13]. Boron has a variety of functions that help fruit crops withstand the negative impacts of environmental stress. These functions include regulating physiological reactions, strengthening stress tolerance mechanisms and promoting optimal plant growth, development and productivity despite difficult growing environments.

Boron-Mediated Stress Tolerance in Fruit Crops

Boron plays a crucial role in enhancing stress tolerance mechanisms in fruit crops through its involvement in various molecular and biochemical processes. In fruit crops, boric acid increases stress tolerance by influencing the expression of stress-responsive genes related to osmotic adjustment, antioxidant defence, hormone signalling and ion homeostasis (Camacho-Cristóbal *et al.*, 2015; Hu *et al.*, 2012) [15, 38]. To orchestrate adaptive responses to environmental stresses, boron-responsive transcription factors and regulatory elements control the expression of genes associated with stress (Hu *et al.*, 2012; Schnurbusch *et al.*, 2010) [38, 64]. In fruit crops, Boron increases the activity of antioxidant enzymes that scavenge reactive oxygen species (ROS) and mitigate oxidative damage under stress circumstances, such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (APX) (Wimmer and Eichert, 2013) [74]. Fruit cultivar's ability to withstand stress and preserve cellular redox equilibrium are both improved by the stimulation of antioxidant defense systems through boron (Goldbach and Wimmer, 2007) [31]. According to (Goldbach and Wimmer, 2007) [31], boron affects the structure and characteristics of fruit crop's cell walls, improving their ability to withstand stress by controlling their extensibility, flexibility and integrity. To reinforce cell walls and provide mechanical support to endure stress-induced mechanical pressures, boron cross-links pectic polysaccharides in the cell wall matrix (Goldbach and Wimmer, 2007) [31]. According to (Camacho-Cristóbal *et al.,* 2015) and (Schnurbusch *et al.,* 2010) [15, 64], boron interacts with plant hormones like auxin, ethylene and abscisic acid (ABA) to modify hormone signalling pathways and stress responses in fruit crops. According to (Schnurbusch *et al.,* 2010) [64] and (Camacho-Cristóbal *et al.,* 2015) [15], boron regulates some physiological processes related to growth, development and stress tolerance. It also affects hormone production, transport and perception. By increasing the activity of nutrient transporters and enzymes involved in food metabolism, boric acid improves nutrient absorption and assimilation in fruit crops (Wimmer and Eichert, 2013) [74]. Enhancing fruit crop resilience to environmental stressors and supporting plant growth and productivity under difficult growing conditions are two benefits of borate-mediated improvements in nutrient absorption and utilization (Wimmer and Eichert, 2013) [74]. Through controlling gene expression, triggering antioxidant defense mechanisms, altering the characteristics of cell walls, controlling hormone signalling pathways and improving nutrient uptake and assimilation processes, boron improves fruit crop stress tolerance. This promotes plant growth, development and productivity in challenging environmental circumstances.

Boron Application Techniques and Agronomic Practices

A sufficient supply of borate is needed for the production of fruit crops and it is necessary for maximizing yield, quality and stress tolerance. The objective of traditional boron fertilization techniques is to guarantee enough boron availability in the soil and fruit crop uptake. According to (Marschner, 2012) [48], conventional boron fertilization frequently uses soil application techniques in which boron-containing fertilizers are mixed into the soil before planting or added as topdressings during the growth season. Boric acid, borax (sodium borate) and boron-containing substances like boron humates and boronated superphosphate are examples of boron fertilizers that are frequently applied to soil (Marschner, 2012; Shorrocks, 1997) [48, 65]. Another common technique to increase fruit crop's boron uptake is foliar spraying of fertilizers, particularly during crucial growth stages including blooming, fruit set and fruit development (Brown *et al.,* 2002; Bellaloui *et al.,* 2009) [9, 13]. To facilitate quick absorption and translocation into plant tissues, boron foliar sprays are usually sprayed as diluted solutions of boron-containing substances such as borax or boric acid (Brown *et al.,* 2002; Bellaloui *et al.,* 2009) [9, 13]. To ensure effective boron uptake and usage by plants, boron fertilizers can be precisely applied using drip irrigation systems straight to the root zone of fruit crops. Fruit crops can receive a consistent and regulated supply of boron from soluble boron fertilizers, like boric acid or borax, by dissolving them in irrigation water and delivering them to the root system via drip lines. As an alternative to traditional fertilization techniques, controlled-release or slow-release boron fertilizers give fruit crops a steady and gradual supply of boron over an extended period (Goldbach and Wimmer, 2007; Wimmer and Eichert, 2013) [31, 74]. To control nutrient release rates, limit leaching losses, improve nutrient usage efficiency and lessen environmental impacts, these fertilizers are usually coated or encapsulated (Goldbach and Wimmer, 2007; Wimmer and Eichert, 2013) [31, 74]. To maximize nutrient balance and improve overall crop nutrition, conventional boron fertilization techniques may also incorporate boron with other vital nutrients or soil amendments (Marschner, 2012; Goldbach and Wimmer, 2007) [31, 48]. To meet the nutritional needs of fruit crops and address numerous nutrient shortages at once, combination fertilizers that contain boron together with nitrogen, phosphorus, potassium and micronutrients are frequently employed (Marschner, 2012; Goldbach and Wimmer, 2007) [31, 48]. Traditional techniques for boron fertilization in fruit crop production include foliar spraying, drip irrigation, controlled-release fertilizers, soil application and combination fertilization. These techniques seek to maximize nutrient uptake and utilization, guarantee sufficient boron supply for fruit crops and improve crop performance and stress tolerance in a range of growth environments.

Evaluation of Innovative Boron Application Techniques

Novel approaches to applying boron have been developed and assessed recently to maximize crop performance in fruit production systems, increase the efficiency of boron uptake and improve nutrient usage. These methods, which include fertigation, nano-boron formulations and foliar spraying, present viable ways to solve the boron deficit and optimize its advantages in fruit crops. By directly applying boron-containing solutions to fruit crop's leaves, a process known as foliar spraying, boron can be quickly absorbed and translocated into plant tissues (Bellaloui *et al.,* 2009; Brown *et al.,* 2002) [9, 13]. Targeted boron delivery to actively growing tissues, a lower chance of soil fixation or leaching and scheduling and application frequency flexibility are only a few benefits of foliar spraying (Bellaloui *et al.,* 2009; Brown *et al.,* 2002) [9, 13]. However, variables including spray coverage, droplet size and ambient conditions may have an impact on how successful foliar spraying is (Bellaloui *et al.,* 2009) [9]. Fertigation is the process of directly applying water-soluble fertilizers, such as boron fertilizers, to the root zone of fruit crops using irrigation systems like drip or sprinklers. Fertigation maximizes nutrient uptake efficiency and reduces losses from leaching or runoff by enabling the exact and uniform delivery of nutrients, including boron, to the root system. Boron fertigation provides flexible and effective nutrient management by allowing for customization to crop growth stages and nutrient requirements. An innovative method for efficiently and precisely supplying boron to fruit crops is the use of nano-boron formulations (Usman *et al.,* 2020; Dimkpa *et al.,* 2017) [23, 70]. The utilisation of nano-boron particles, either in isolation or enclosed within nanocarriers, has several benefits, including improved solubility, stability and specific boron delivery to plant tissues (Usman *et al.,* 2020 [70]; Dimkpa *et al.,* 2017) [23]. According to (Usman *et al.,* 2020 [70]; Dimkpa *et al.,* 2017) [23], nano-boron formulations can decrease environmental losses, increase the efficiency of boron uptake and use, and lessen the possibility of boron toxicity or deficiency in fruit crops. To assess the effectiveness, safety and long-term effects of nano-boron formulations on the health of the soil and the productivity of fruit crops, more investigation is necessary (Dimkpa *et al.,* 2017) [23]. Cutting-edge methods for applying boron, including as fertigation, foliar spraying and nano-boron formulations, present viable ways to maximize nutrient management, boost crop performance and increase boron uptake efficiency in fruit production systems. By using these methods, it is possible to solve boron toxicity or deficiency problems and optimize boron's advantages for the growth of fruit crops.

Optimal Boron Dosages and Timing

For fruit crops to grow, develop and yield as best they can, boron must be applied at the right times and in the right amounts. However, depending on the kind of fruit crop and its stage of growth, varied boron requirements may apply. Oranges, lemons and grapefruits are examples of citrus fruits with moderate to high boron requirements, particularly during flowering, fruit set and the early phases of fruit development (Marschner, 2012) [48]. Depending on the soil boron status, anticipated fruit output and environmental factors, the ideal boron dosages for citrus crops usually vary from 0.5 to 2 kg per hectare (Marschner, 2012) [48]. To efficiently meet citrus boron requirements, foliar boron administration throughout flowering and fruit development stages combined with soil application before flowering is advised (Marschner, 2012) [48]. For best growth and fruit development, pome fruits (apples, pears, etc.) need moderate doses of boron at flowering and the early phases of fruit development are crucial times to apply boron (Brown *et al.*, 2002; Marschner, 2012) [13, 48]. Depending on soil boron availability and crop requirements, the ideal boron dosages for pome fruits usually range from 0.5 to 1 kg of boron per hectare, delivered either as soil amendments or foliar sprays (Brown *et al.*, 2002; Marschner, 2012) [48]. According to (Brown *et al.*, 2002; Marschner 2012) [13, 48], split administrations of boron before and after flowering enable continuous boron availability during important growth stages of pome fruits. Depending on the soil type, cultivar and environmental factors, stone fruits—peaches, plums, and cherries, for example—have different boron requirements. During the flowering and fruit set stages, boron levels are crucial (Marschner, 2012) [48]. Higher doses are advised for boron-deficient soils or high-yielding orchards. Optimal boron dosages for stone fruits normally range from 0.3 to 1 kg of boron per hectare, administered as soil or foliar sprays (Marschner, 2012) [48]. For stone fruit crops, boron administration prior to flowering and fruit set ensures sufficient boron availability (Marschner, 2012) [48]. Low to moderate boron requirements are found in berries, such as raspberries, strawberries and blueberries. During the stages of fruit growth and flowering, boron requirements become crucial (Bellaloui *et al.*, 2009) [9]. Depending on soil boron levels and crop requirements, the ideal boron dosages for berry crops are usually between 0.2 and 0.5 kg per hectare, administered as foliar sprays or fertigation (Bellaloui *et al.*, 2009) [9]. In order to efficiently meet the boron requirements of berry crops, split treatments of boron are applied before and after flowering (Bellaloui *et al.*, 2009) [9]. A variety of factors, including crop boron requirements, soil boron status, environmental circumstances and management approaches, influence the ideal boron dosages and timing for various fruit crop species and growth phases. In fruit production systems, adequate boron management techniques—such as soil and foliar sprays at the right growth stages—are necessary to guarantee the best possible fruit yield, quality and resilience to stress.

Integration of Boron Application

Applying boron as part of holistic agricultural management techniques can improve plant health, maximize nutrient availability and strengthen stress tolerance mechanisms in fruit crops. Applying boron in conjunction with other farming techniques has synergistic effects that raise crop resilience and productivity overall. Boron application can be combined with other soil health management techniques, such as adding organic amendments, growing cover crops and reducing tillage to improve soil structure, microbial activity and nutrient cycling. This will increase boron availability and fruit crop uptake (Liu *et al.*, 2013; Marschner, 2012) [44, 48]. Nutrient deficits and the stress they cause on fruit crops are less likely to occur in healthy soils with balanced nutrient levels, which encourage ideal plant growth, development and stress resilience (Marschner, 2012) [48]. Enhancing boron absorption efficiency and stress tolerance in fruit crops can be achieved by combining boron administration with effective irrigation management techniques including drip irrigation, deficit irrigation and controlled deficit irrigation. These techniques can maximize the delivery of water and nutrients to fruit crops. Managed irrigation techniques guard against boron shortages brought on by water stress and reduce leaching losses, guaranteeing constant boron availability for fruit crop development and growth. Applying boron in conjunction with balanced nutrient management techniques, such as fertilization, soil testing and nutrient monitoring, guarantees fruit crops receive an adequate supply of nutrients and reduces the possibility of nutrient deficiencies or imbalances, which can worsen stress susceptibility (Marschner, 2012) [48]. In fruit production systems, integrated nutrient management strategies improve plant health, stress tolerance and yield stability by optimizing boron absorption and utilization efficiency (Marschner, 2012) [48]. By strengthening plant defense mechanisms and lowering susceptibility to pest and disease outbreaks, boron application in conjunction with integrated pest and disease management (IPM) techniques, such as biological control, cultural practices and pest-resistant cultivars, improves fruit crop resilience to biotic stresses (Gill and Tuteja, 2010; Marschner, 2012) [30, 48]. Plants that are in good health and have sufficient amounts of boron have improved resistance to pest and disease attacks, which reduces the likelihood of output losses and production hazards (Gill and Tuteja, 2010; Marschner, 2012) [30, 48].

Sustainable fruit production system resistant to the effects of climate change are promoted by including boron treatment in climate-smart agriculture methods, such as agroforestry, drought-tolerant crop types and soil carbon sequestration (Lal, 2004) [42]. In conjunction with climate-resilient agricultural techniques, enhanced stress tolerance mechanisms enhanced by boron reduce the negative impacts of climate variability on fruit crops, guaranteeing farmers predictable yields and a living wage (Lal, 2004) [42]. Fruit crop stress resilience can be improved holistically by combining boron treatment with other agricultural strategies such as climate-smart agriculture, pest and disease control, nutrient management, irrigation management, soil health management and nutrient management. By maximizing boron availability, enhancing plant health and vigour, and reducing the effects of stress, these combined techniques provide robust and sustainable fruit production systems.

Impact of Boron on Fruit Crop Yield and Quality

The application of beryllium has a significant impact on the production of fruit crops by modulating several physiological processes that are associated with fruit size, uniformity and yield. For fruit crops to flourish, pollinate and set fruit as best they can, boron is necessary (Brown *et al.,* 2002; Marschner, 2012) [13, 48]. According to (Brown *et al.,* 2002) and Marschner (2012) [13, 48], sufficient boron availability enhances pollen germination, pollen tube expansion and fertilization, which improves fruit set and raises the possibility of yield. In fruit crops, a shortage of boron during the crucial blooming stages can lead to uneven fruit growth, low yield and poor fruit set. Higher fruit yields and increased crop productivity can be achieved by applying boron fertilizers, which can overcome production limits brought on by boron deficiency (Brown *et al.*, 2002; Marschner, 2012) [13, 48]. Fruit size and shape are influenced by boron through its effects on cell division, expansion and differentiation processes in developing fruit tissues. In fruit crops, ideal boron levels encourage cell elongation and expansion, which increases fruit size and marketability. On the other hand, a lack of boron can limit cell division and growth, leading to smaller, deformed fruits that are worth less on the market. Applying boron can ensure appropriate fruit size and quality attributes by promoting uniform fruit development and correcting size-related anomalies (Bellaloui *et al.*, 2009) [9].

Boron application encourages balanced growth and development throughout fruit clusters or trees, which helps to maintain fruit uniformity. To maintain regular fruit development and maturation inside fruiting structures, boron is essential for hormone regulation, carbohydrate metabolism and nutrient partitioning (Goldbach and Wimmer, 2007) [31]. Improved fruit uniformity and marketability are the outcomes of balanced boron nutrition, which reduces variances in fruit size, shape and quality among individual fruits (Goldbach and Wimmer, 2007) [31]. Applying borate to fruit crops has a major impact on fruit output, size and homogeneity because it controls vital physiological processes related to nutrition metabolism, cell growth, flower development and fruit set. Increased fruit size, uniformity and optimal production potential are all facilitated by an adequate boron supply, which raises crop productivity and market value.

Influence of Boron on Fruit Quality Attributes

The elements of fruit quality that are most affected by boron are its nutritional makeup, flavour and shelf life. Fruit development, composition and post-harvest features are directly impacted by its participation in several physiological processes. In fruit crops, boron is necessary for the metabolism of proteins, carbs and nucleic acids, which affects the production and accumulation of critical nutrients. Sufficient quantities of boron facilitate the absorption and application of key minerals including calcium, magnesium, and potassium, which are critical for the nutritional value and quality of fruit. Fruits with low nutrient contents and nutritional imbalances caused by a lack of boron may not be as palatable to consumers or have the same nutritious value. On the other hand, boron treatment can improve fruit quality and health benefits by guaranteeing balanced nutrient uptake and metabolism, which improves fruit nutritional composition (Brown *et al.*, 2002; Bellaloui *et al.,* 2009) [9, 13]. Through its roles in the creation of organic acids, the metabolism of sugar and the formation of volatile compounds, boron affects the flavor of the fruit. The accumulation of organic acids, such as citric and malic acids and sugars, such as glucose and fructose, is facilitated by optimal boron levels and contributes to the sweet and tart flavours seen in ripe fruits (Brown *et al.,* 2002; Marschner, 2012) [13, 48]. Furthermore, boron improves the synthesis of volatile molecules in fruits that give them their scent and flavour, which increases the fruit's sensory appeal and acceptance by consumers. Fruits lacking in Boron may have changed flavour profiles, less sweetness and a stronger scent, which will affect their marketability and appeal to consumers. Applying boron can lessen these effects by encouraging the best possible development of flavour and improving the flavour and aroma characteristics of fruit (Brown *et al.*, 2002; Marschner, 2012) [13, 48]. By controlling membrane integrity, cell wall structure and post-harvest physiological activities, boron affects the shelf life of fruit. For the synthesis and cross-linking of cell wall constituents including pectins and hemicelluloses, which offer structural support and keep fruit solid during storage, enough boron levels are necessary. A lack of boron can cause fruit to soften and decay more quickly, have weaker cell walls that are more vulnerable to mechanical damage and have a shorter shelf life and lower market value. By fortifying fruit cell walls, lowering post-harvest losses and prolonging storage times, boron application extends fruit shelf life and ensures prolonged freshness and quality preservation (Brown *et al.*, 2002) [13]. Through the regulation of vital physiological processes in fruit crops, boron has a substantial impact on fruit quality traits such as nutritional composition, flavour and shelf-life. A balanced nutritional content, improved flavour development and extended shelf life are all benefits of optimal boron nutrition, which raises fruit quality and customer satisfaction.

Comparative Analysis of Boron's Impact

Depending on genetics, habitat, soil characteristics and cultural techniques, boron's effects on fruit crop kinds might differ greatly. Comparing the effects of boron on various fruit crop kinds and growing environments offers important insights into the range of responses and the significance of specialized boron management techniques. Variations in boron sensitivity and tolerance between fruit crop varieties are due to genetic variations in boron uptake mechanisms, transport processes and physiological responses (Brown *et al.*, 2002) [13]. Because of inherent characteristics like root shape, ion uptake kinetics or metabolic pathways involved in boron consumption, some cultivars may be more prone to boron deficit or toxicity. Comparative research on several fruit crop varieties, including strawberries, oranges, grapes and apples, can clarify genotype-specific boron responses and help choose boron-tolerant cultivars for various growing environments (Brown *et al.*, 2002) [13]. Growing environments affect the availability, efficiency and utilization of boron by fruit crops. These characteristics include soil pH, moisture content, temperature regimes and climatic influences. An examination of the impacts of boron in different environmental circumstances, such as humid versus arid climates, alkaline versus acidic soils, or rain-fed versus irrigated systems, can show how environmental factors interact to affect crop performance and boron nutrition. Comprehending the interplay between boron and environmental factors is crucial to formulating boron management strategies that are particular to a given site and customized to the growing environment (Marschner, 2012) [48]. Boron availability, mobility, and uptake by fruit crops are influenced by agricultural management techniques, such as soil additives, fertilization plans and irrigation control. An examination of the relative effects of boron under various management regimes—for example, conventional versus organic farming, drip versus flood irrigation, or mineral versus organic fertilizer applications—can clarify the relative effectiveness of various strategies for maximizing boron nutrition and crop productivity. Enhancing nutrient use efficiency and reducing environmental consequences can be achieved through integrated nutrient management strategies that take into account the relationships between boron and other nutrients (Marschner, 2012) [48]. A comparative examination of the effects of boron on various fruit crop varieties and growing environments yields important information about interactions between genotype and environment, the effects of management, and the creation of specialized boron management plans. Bovine nutrition programs must incorporate genetic, environmental and management aspects to maximize fruit crop output, quality and sustainability in a variety of agricultural systems.

Ecological Implications and Risk Assessment

Environmental fate of boron in soil and water systems

Complex mechanisms that are impacted by soil characteristics, hydrological variables and human activity determine the environmental fate of boron in soil and water systems.

Soil Fate: Following application, boron experiences several changes in the soil, such as leaching, precipitation, desorption and adsorption. Soil pH, organic matter content, texture and mineral composition are some of the parameters that affect the fate of boron in soil. According to (Alloway 2013) [2], boron tends to form insoluble compounds with magnesium and calcium in alkaline soils, which decreases its availability for plant uptake. On the other hand, boron may continue to be more soluble and susceptible to leaching in acidic soils, raising the possibility of groundwater contamination. According to (Alloway 2013) [2], sorption-desorption processes control boron's mobility and bioavailability in soil, influencing its persistence and possible effects on the environment.

Water Fate: Through leaching or runoff processes, boron can travel through soil profiles and reach surface water bodies or groundwater. Hydrological dynamics, such as soil permeability, precipitation patterns and land use practices, influence the destiny of boron in water systems. Elevated boron levels may build up in surface water or shallow groundwater in regions with extensive agricultural operations or high irrigation water boron intake, endangering aquatic ecosystems and public health. Geochemical processes including sedimentation, adsorption onto particulate matter and biological uptake by aquatic species all have an impact on the destiny of boron in water bodies (Alloway, 2013) [2].

Environmental Implications: Human well-being, agricultural sustainability and ecosystem health are all impacted by the environmental fate of boron in soil and water systems. Increased boron concentrations in the soil can cause plants to exhibit toxic symptoms, which can have an impact on soil fertility and crop productivity. Excessive boron concentrations in water systems can harm aquatic life, interfere with the functioning of ecosystems and endanger human health by contaminating drinking water. To ensure the sustainable use of boron-containing products in industry and agriculture and to reduce environmental impacts, it is imperative to create effective management methods based on an understanding of the environmental fate of boron (Alloway, 2013) [2]. The environmental fate of boron in soil and water systems involves complex interactions influenced by soil properties, hydrological processes and anthropogenic activities. A comprehensive understanding of boron's fate and transport mechanisms is essential for assessing environmental risks and implementing appropriate management measures to safeguard ecosystems and human health.

Strategies for minimizing environmental impact

Optimizing boron management techniques to guarantee effective nutrient utilization while lowering risks of environmental contamination is one way to maximize boron efficacy in fruit crop development while limiting its negative effects on the environment. Soil and Water Testing: Regular testing of the soil and water aids in establishing baseline boron levels and evaluating possible hazards of toxicity or deficiency in the production of fruit crops. Analyses of the soil and water are very helpful in creating site-specific boron management plans that are suited to the local environment, maximizing nutrient applications and reducing environmental effects. Targeted boron application is made possible by the use of precision agricultural techniques, such as variable rate application and site-specific nutrient management, which take into account the temporal and spatial variability of crop and soil requirements. In fruit crop production systems, precision boron treatment lowers environmental risks, maximizes nutrient use efficiency and decreases nutrient losses through leaching or runoff (Marschner, 2012) [48]. Applying boron in conjunction with other nutrient management techniques, such cover crops, organic amendments, and balanced fertilization, encourages nutrients to work in concert, improves soil fertility and lessens dependency on artificial inputs (Marschner, 2012) [48]. In the cultivation of fruit crops, balanced nutrient management reduces the possibility of nutrient imbalances or toxicities, maximizes boron efficacy and lessens environmental effects (Marschner, 2012) [48].

Water-efficient irrigation techniques, like deficit irrigation, drip irrigation and micro-irrigation, can assist limit water and nutrient losses, increase the effectiveness of fertilizer uptake and lower the hazards of boron leaching on the environment. Accurate application of water and nutrients to fruit crops guarantees the best possible availability of boron while preserving water supplies and reducing environmental effects (Alloway, 2013) [2]. Enforcing safe use methods in the development of fruit crops, monitoring boron levels in soil, water and food items, and assessing potential threats to ecosystems and human health are all made possible by the implementation of environmental monitoring programs and regulatory procedures. It is easier to identify environmental issues early and take action to stop negative effects when boron concentrations in environmental compartments are monitored and threshold limits are set (Alloway, 2013) [2]. To enhance fertilizer use efficiency, conserve resources and protect environmental quality, strategies for minimizing environmental effects while maximizing boron efficacy in fruit crop production involve using integrated practices, precision nutrient management and regulatory measures.

Future Directions

To improve crop resilience and further our understanding of boron-mediated stress relief in fruit crops, it is critical to identify research objectives and knowledge gaps. The poor understanding of the molecular mechanisms behind boron-mediated stress tolerance, the unpredictability of crop-specific responses to boron administration and the lack of research on novel delivery techniques such as foliar spraying and nano-boron formulations are among the major knowledge gaps. Furthermore, little is known about how boron interacts with the environment, the dangers of using it excessively and how to incorporate boron management techniques into sustainable farming methods. Clarifying molecular pathways, comparing various crop kinds, refining application methods, evaluating environmental effects and combining boron tactics with sustainable agriculture should be the top priority for research. Addressing these gaps will enable the development of evidence-based interventions to mitigate environmental stressors and enhance fruit crop productivity sustainably.

Conclusion

In the context of climate change adaptation, boron treatment emerges as a critical tactic for improving horticultural sustainability. Amidst increasingly uncertain weather conditions, boron presents a promising option for enhancing fruit crop resilience, productivity and quality through its diverse roles in plant physiology and stress mitigation. Boron administration protects potential yield by minimizing the negative impacts of environmental stresses such as heat, drought and salinity on reproductive processes by fostering ideal flower growth, pollen germination and fruit set. The deeply regulated process of boron uptake, transport and distribution in plants establish the optimal usage for growth, development and cellular homeostasis. In addition, boron improves fruit quality characteristics like size, flavor and shelf life through its role in cell wall production, membrane integrity and nutrient metabolism, which guarantees market competitiveness and customer pleasure. Approaches like foliar application, fertigation and nano-boron formulation are valid means to overcome the deficiencies in boron and maximize the benefits in fruit crops. More importantly, by reducing environmental effects and increasing resource efficiency, boron application provides a sustainable alternative for climate-smart agriculture. Boron application can be combined with other soil management techniques, such as adding organic amendments, reducing tillage, growing cover crops, to improve soil structure and nutrient cycling. Application of boron with proper dosing and time can improve yield and quality and ensures better nutrient uptake by plants to improve deficiencies, soil fertility in sustainable agricultural production. Boron is an important factor for the fruit quality characteristics because the comparison studies proved that boron is critical in determining the quality and quantity of fruit crops. It was observed that environmental behavior of boron in the soil and water mediums depends upon fate of boron in these two environments. There is a need to understand the mobility and persistence of boron in the soil and water since it has extreme importance as the environmental point of view. Definite soil and water testing, precise applications of boron, integrated nutrient management along with strategic irrigation practices is the key for effective agricultural resource management and these are coupled with environmental monitoring and regulations for sustaining agricultural productivity along with environment safekeeping. Through the prioritization of research endeavours, the integration of boron strategies with sustainable practices, and the resolution of knowledge gaps, stakeholders may effectively leverage the potential of boron to construct robust fruit crop systems that not only survive in a changing climate but also minimize environmental footprints. In the end, boron application is a fundamental component of climate-smart horticulture, providing a way forward in the face of escalating difficulties towards food security, economic development and environmental stewardship.

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