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Boron Impact on Maize Growth and Yield: A Review

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

Maize (*Zea mays* L.) is a vital crop, contributing significantly—at least 30%—to global dietary energy intake and biofuels and ethanol production. This review article delves into the dynamic interplay between boron (B) and maize growth, yield, and agricultural sustainability. Boron, a crucial micronutrient, is pivotal in essential physiological processes such as root development, leaf expansion, and cob formation. These processes are fundamental for ensuring the vigour and productivity of maize crops. Conversely, boron deficiency manifests as thinner leaves with reduced chlorophyll content, compromising plant health, and hindering yield potential. Maintaining adequate boron levels, particularly during reproductive stages, is critical for mitigating the risk of abnormal ears and maximizing the quantity and quality of maize production. Emerging research underscores the significance of foliar boron application at various growth stages of maize, which stimulates growth, facilitates cell wall development, and increases leaf area. This translates to improved light interception and photosynthetic efficiency, ultimately contributing to increased plant vigour and biomass accumulation. Furthermore, exploring innovative approaches for sustainable boron management is crucial. This includes precision fertilization techniques and biofortification strategies to ensure optimal maize production while minimizing environmental impacts. By gaining a deeper understanding of the complex relationship between boron and maize, farmers can develop customized fertilization plans that utilize strategic foliar boron application. This approach unlocks maize's full yield potential and contributes to sustainable agricultural practices, supporting global food security.

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Keywords: Boron; maize; growth; micronutrients.

ABBREVIATIONS

NIP: Nodulin Intrinsic Protein

1. INTRODUCTION

Maize is a crucial crop globally, significantly impacting the agri-food system. It is the world's second most widely grown crop, annually cultivated on an estimated 197 million hectares of land. Maize is a versatile multipurpose crop, serving as a significant food source in sub-Saharan Africa and Latin America [1]. It is primarily used as feed globally and consumed as human food con-tributes over 20% of food calories [2]. Its production has surged due to rising demand, and it is set for continued growth, with global consumption patterns showing its importance as a feed and food. Maize is also used for industrial purposes, constituting around 22% of its consumption, with 83% of its production being used in the starch and biofuel industries. The global consumption pattern of maize reflects its versatility and significance as a food, feed, and industrial crop [3]. The global importance of maize diversity is recognized, and its impact on biodiversity, water use, ecosystem services, livelihoods, food security, and health is a subject of ongoing research and policy consideration.

Boron (B) exerts its effects on plant growth and development through various mechanisms. One mechanism is the regulation of B transport systems in the plant. The boric channel NIP5;1 and the borate transporter BOR1 are in charge of efficiently taking in and moving B. When there is a lot of B in the environment, they are turned off, which helps keep B from being harmful [4]. B also interacts with other elements in the plant, such as macronutrients and micronutrients, affecting their uptake and metabolism [5]. Excess B can lead to morphological and anatomical changes in plants, impairing cell wall formation and disrupting membrane systems [6]. B deficiency stops roots from growing longer and changes hormone production and signalling, mainly the movement of auxin in the root elongation zone [7]. Addition-ally, B toxicity triggers the production of reactive oxygen species, which the antioxidant defense system via abscisic acid and salicylic acid can detoxify [8] These mechanisms highlight the importance of boron in plant growth and development and provide insights for developing strategies to improve B use efficiency and tolerance in crops.

Boron application has a positive effect on hybrid maize yield. Foliar application of B has been shown to have significant benefits for maize plants. It has been found that foliar application of B can increase plant height, number of leaves per plant, dry weight of the plant, number of cobs per plant, number of grains per cob, and yield parameters such as seed index, grain yield, and straw yield [9,10]. Additionally, foliar supplementation with B has been found to increase the activities of antioxidant enzymes, reduce stress markers, and stimulate root growth, resulting in a higher harvest index and yield [11]. Furthermore, foliar application of B can affect carbon fixation, metabolism, and allocation belowground, as well as improve plant uptake of other essential nutrients such as zinc [12]. Overall, foliar application of B provides an effective method for supplying this essential nutrient to maize plants, leading to improved growth, yield, and stress tolerance. The review aims to explore the physio-logical impact of B on maize plants, with a particular focus on its effects on growth, development, and overall productivity. It will include results from a wide range of experiments that looked at how they interact with other nutrients, how to make varieties that use B more efficiently, and how to use precision agriculture technologies.

2. LITERATURE REVIEW

Reviewed existing research on the role of boron in maize

2.1 Global Significance of Maize Cultivation

Maize, also known as corn, reigns supreme as the second most cultivated crop globally, occupying a staggering 197 million hectares of land. Its adaptability and high yield make it a crucial player in global food security, especially for farmers in low and lower-middle-income countries [13]. The diverse agro-ecological conditions where maize thrives are reflected in its many rainfed mega-environments. From wet lowlands to dry highlands, maize varieties have been developed to withstand these varying climates [14]. These varieties display distinct characteristics, with differences in susceptibility to pests and diseases, maturity rates, and tolerance for heat and drought. Maize serves as a vital staple crop, particularly in developing regions of Africa, Latin America, and Asia. In these areas, it contributes a minimum of 30% of dietary energy for a significant portion of the population [15]. It's no surprise farmers favor maize: its exceptional productivity and adaptability to diverse conditions make it ideal for regions with limited land and high population densities [15]. From its Mesoamerican origins, maize cultivation has expanded dramatically, becoming a fundamental food source in many regions, including sub-Saharan Africa [15]. Geographically, maize production is heavily concentrated in the Americas and Asia, each accounting for over a third of the total area cultivated globally. Africa follows with a significant share (around one-fifth), while Europe contributes a smaller proportion [14]. Beyond its role as a food source, maize holds cultural significance in various locations. Interestingly, maize has risen to prominence in Asia, particularly in China, where it has surpassed rice and wheat to become the dominant cereal crop. Asian maize production has witnessed substantial growth, with countries like Indonesia, India, the Philippines, Pakistan, and Vietnam emerging as key players on the global stage. Finally, maize contributes significantly to the production of biofuels and ethanol. The booming biofuel industry, particularly in the United States, has spurred a rise in maize demand for this specific use [14]. So, the review highlights key points such as the significance of maize in low-income countries and its diverse uses beyond food.

2.2 Economic Impacts of Boron Deficiency in Maize Cultivation

B deficiency in maize cultivation has significant economic impacts due to reduced yield and quality. Studies show that boron deficiency leads to yield losses and poor quality in maize crops, affecting various continents like Pakistan, Turkey, and beyond [16,17]. Research highlights that B plays a crucial role in plant development, and its deficiency results in stunted growth, reduced root and shoot growth, and male sterility, ultimately impacting grain yield [18]. Optimal B application levels are essential to mitigate these economic impacts. Addressing boron deficiency through proper management practices is crucial for maximizing maize production and ensuring economic sustainability in agriculture.

2.3 Boron Deficiency Symptoms in Maize

The symptoms of B deficiency in maize include irregular distribution of kernels, a general reduction in growth, short and bent cobs, barren ears, poor kernel development, yellow or white spots on leaves with brown waxy raised streaks, stunted growth, and shortened internodes. These symptoms are typically more pronounced in the youngest leaves. B deficiency in maize can be observed in various stages of plant growth, such as tasseling and silking stages. It is important to address B deficiency through appropriate fertilization methods to ensure improved crop development and increased yield.
Boron deficiency in maize can lead to a range of symptoms, including:

- Irregular distribution of kernels and a general reduction in growth
- Short and bent cobs with missing kernels
- Barren ears and poor kernel development
- Yellow or white spots on leaves with brown waxy raised streaks
- Stunted growth with shortened internodes
- Boron deficiency symptoms are most noticeable in the youngest leaves of the maize plant [19-21].

Multiple studies document the detrimental effects of boron (B) deficiency on plant reproductive systems, particularly in maize. B deficiency disrupts stamen development, leading to deformed pollen and male sterility, ultimately manifesting as barren cobs and yield reduction. Research by Lordkaew [22] and Struckmeyer [24] highlights B's crucial role in anther development and floret fertility, emphasizing the critical period for B uptake to prevent irreversible damage. B deficiency in maize can significantly impact root growth. The research indicates that under B deficiency, maize plants exhibit shorter roots and a reduction in lateral root number [25]. This deficiency can lead to root growth cessation, as well as the disappearance of the root cap, ultimately inhibiting root growth. The cessation of cell division in the apical meristem due to B deficiency is a key factor in inhibiting root growth [26]. Additionally, excessive levels of B have been shown to weaken roots, causing decreased root growth in maize plants. The negative effects of B deficiency on root growth are particularly pronounced, as root growth is more sensitive to B deficiency than shoot growth. Therefore, ensuring adequate B levels is crucial for the healthy root development of maize plants [23,27]. Furthermore, Wilder et al. [25] demonstrate the impact of B deficiency on yield through abnormal development of reproductive structures, resulting in smaller cobs with fewer kernels. The study pinpoints the link between B deficiency and male sterility, highlighting its importance for viable pollen and proper seed development. They emphasize the critical role of maintaining adequate B levels during the reproductive phase to maximize yield.

2.4 Factors Affecting Boron Availability in Soil

Factors that impact the accessibility of B in soil encompass various soil characteristics, namely pH, texture, organic matter content, and clay content [28]. Furthermore, B availability can be influenced by additional factors such as temperature, moisture content, and the specific plant species [29]. Additionally, B availability decreases with an increase in soil pH, except in saline-sodic soils [30]. It should also be noted that the depth of the soil plays a significant role, as the concentration of available B decreases with increasing soil depth [31]. In addition, environmental elements like topography, climate, and vegetation have the potential to affect the accessibility of B in the subsoil [32]. Moreover, the application of fertilizers, particularly those containing phosphorus and potassium, can contribute to the concentration of B that is available to plants in the soil. The process of B adsorption and desorption in soil is influenced by factors such as pH, salinity, sand content, clay content, total organic carbon, total nitrogen, and cation exchange capacity. In conclusion, comprehending these factors is paramount for effectively managing the availability of B in soil and ensuring optimal growth and yield of crops.

2.5 Maize Response to Boron under Different Soil Environmental Condition

2.5.1 Different methods of boron application

There are several methods of B application in agriculture, each with its own advantages and considerations. The main methods include soil application, foliar spray, fertigation, and seed dressing. Here's a brief overview of each method:

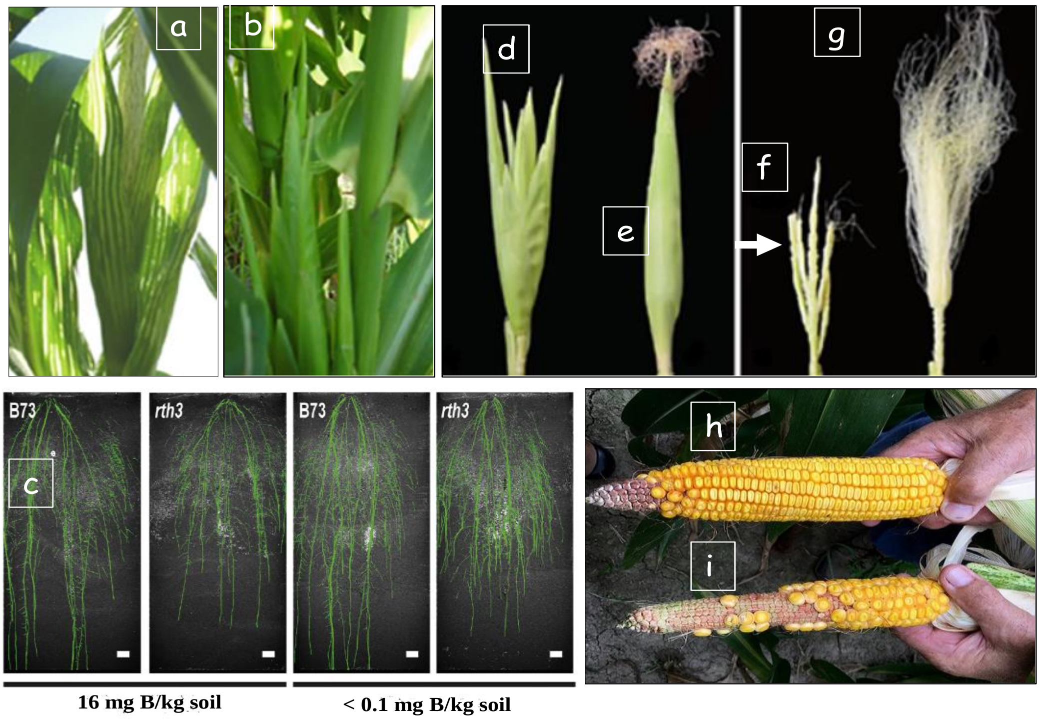

Fig. 1. Symptoms of B deficiency of maize grown without added B showing: white stripes or transparent streaks on leaf lamina (a), multiple ears (b), root growth (c), short sillk [d, f- arrow, removed husk) compared with normal ear (e, g: ear after removal of husk] and healthy and B deficiency corn ear (h, i)

Source: [22-23]

Soil Application: Soil application of B in maize has been studied in several papers. B can be applied to the soil as a solid or liquid. It is typically broadcast before planting or during crop growth. One study found that the application of B and zinc to the soil increased maize grain yield in soils with low B and zinc contents [33]. Another study investigated the effect of soil application of zinc and foliar application of B on the growth and yield of maize. It was found that the application of 15 kg of zinc with 1.5% B as a foliar spray resulted in increased plant height, number of leaves per plant, plant dry weight, number of cobs per plant, number of grains per cob, and grain yield [10]. Another study showed that the treatment of 100 ppm B combined with 700 ppm silicon significantly increased plant height, number of leaves per plant, plant dry weight, and yield attributes in maize [34,35]. Finally, a study on sandy loam soils with different levels of B found that the non-specifically adsorbed B fraction was higher after the application of B, and the plant available form of boron included the non-specifically adsorbed fraction, which coincided with the high demand for B by maize during the vegetative phase [36].

Foliar Spray: This method involves applying a B solution directly to the leaves of the plant. Foliar application is effective for quickly correcting B deficiencies and is especially useful during critical plant growth stages. Foliar application of B has a positive effect on the growth and yield of maize. Treatment with B at 4 kg/ha and Panchagavya at 4% produced maximum plant height, plant dry weight, number of cobs per plant, cob yield with and without husk, and green fodder yield [34]. Another study found that foliar application of B at 0.3% resulted in significantly higher growth parameters such as plant height, plant dry weight, and crop growth rate, as well as yield attributes like number of cobs per plant, number of grains per cob, and grain yield [37]. Additionally, the foliar application of B at 0.6% along with zinc and iron increased plant height, plant dry weight, crop growth rate, number of leaves per plant, number of cobs per plant, and grain yieid [38]. These findings suggest that foliar application of B can enhance the growth and yield of maize.

2.6 Effect Boron on Maize Growth and Development

Boron plays a crucial role in the physiology and function of maize. B deficiency can lead to shorter roots, reduced lateral root number, and a significant impact on metabolic and physiological processes, ultimately affecting the growth, development, and yield of maize [25] (Fig. 2-a, b, & c). Increasing B concentration led to increased CO2 fixation and transport. The effect of CO2 fixation on root growth of maize is a complex interplay influenced by various factors.

CO2 fixation, primarily through photosynthesis, provides the energy and carbon sources necessary for plant growth, including root development. Increased levels of CO2 can stimulate photosynthesis, leading to enhanced root growth in maize. B levels on the growth of different plant tissues in maize studied by Wilder et al., [25] found that B is crucial for root growth. Root mass increased significantly with normal B levels (0.05 mM) compared to no B. However, excess B (0.5 mM) significantly reduced root mass (Fig. 2d). However, when looking at root morphology and anatomy in boron-deficient conditions, Li et al. [39] found that both the primary and lateral root lengths were significantly shortened (Fig. 2e), compared to treatment with +B.

Boron application had a positive effect on leaf area of maize. In one study, the recommended dose of NP2O5K2O + Zn + B resulted in a significantly higher leaf area index (LAI) compared to other treatments [38]. Another study found that foliar application of B had a positive but statistically insignificant effect on plant characteristics, including leaf area, during early leaf stages [40]. Addition-ally, a field experiment showed that the treatment with B3 (100 ppm) + Si3 (700 ppm) significantly increased plant height and the dry weight of the plant, which indirectly indicates an increase in leaf area [34]. Another study showed that leaf area per plant increased by 10.49% and 10.87% in the presence of B application compared to the control. Additionally, the application of foliar B at the fourth leaf stage produced 8.1% and 8.42% taller plants compared to the control plots. The increase in leaf area was attributed to the role of B in promoting plant growth, root and shoot elongation, and the production of cell wall, which ultimately enhanced the leaf area and availability of photosynthates for crop growth [41]. B deficiency in maize can lead to changes in the nutritional content of maize leaves. B deficiency can result in thinner leaves, which may have lower chlorophyll contents [25]. The application of B, particularly through foliar spray, has been shown to increase chlorophyll contents, which in turn can enhance the leaf area and availability of photosynthates for crop growth [42].

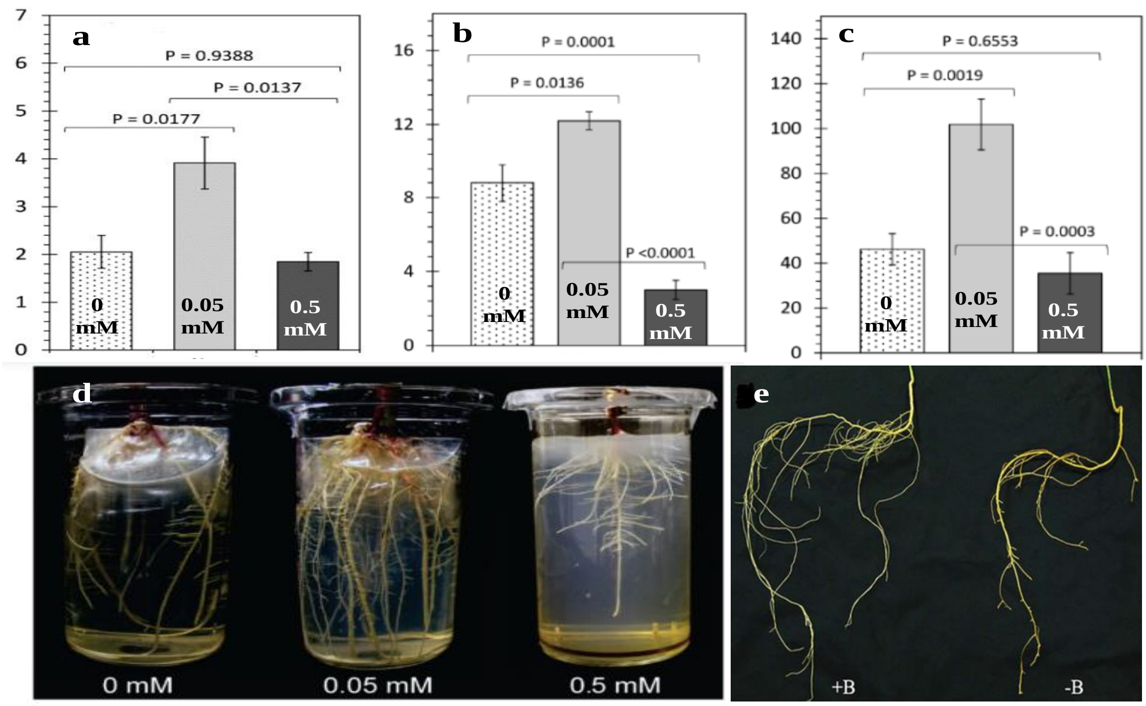

Fig. 2. Effect of B at different concentration (0 mM, 0.05 mM and 0.5 mM) on root mass showing: grams fresh weight of root (a), number of non-lateral roots (b), number of lateral roots (c), roots at different concentration of boron (d). Root growth with and without boron (e)
Source: [36]. Source: [39]

B application has been shown to have a positive effect on plant height in maize. The foliar application of B at various growth stages has been found to increase plant height in maize plants [41]. The increase in plant height is attributed to the role of B in promoting cell differentiation and the production of cell walls, which promotes plant growth and root and shoot elongation [41]. Additionally, the application of B at a rate of 0.6 kg/ha has been shown to significantly in-crease the cob length, cob diameter, and grain yield of maize, which are all related to plant height [5]. The effect of B on the plant height of maize varied across the different studies. Kumar et al. [34] found that treatment B3 (100 ppm) + Si3 (700 ppm) significantly increased plant height. Another study also reported that application of B (4 kg/ha) and Panchagavya (2 sprays of 4%) produced maximum plant height [37]. On the other hand, Dawson found that T9 with foliar application of IAA (90 ppm) and B (1.5%) recorded higher plant height [43]. Additionally, Sai Ram and Dawson reported that application of 15 kg Zinc with B 1.5% as foliar spray recorded highest plant height [10]. Lastly, Kumar et al. [9] found that treatment T9-Misthi + 0.3% B foliar application was recorded significantly higher plant height. These findings demonstrate the positive effect of B application on the growth and yield of maize plants, including plant height.

2.7 Effect Boron on Maize Yield

Boron plays a crucial role in the flowering, yield components, and grain yield of maize. B application has a positive effect on maize cob size. Treatment combinations of B with different levels of zinc and other nutrients resulted in increased cob length and weight. In one study, the treatment with B (4 kg/ha) and Panchagavya (2 sprays of 4%) produced the highest weight of cobs with husk (44.85g) and cob yield with husk (7.48 t/ha) [9]. Another study found that treatment with Misthi variety and 0.3% B foliar application resulted in the highest cob length (18.5 cm) and grain yield (9.5 t/ha) [37]. Additionally, the application of 15 kg zinc with 1.5% B as a foliar spray recorded the highest number of grains per cob (523.93) and grain yield (6.33 t/ha) [9]. These findings suggest that B application, in combination with other nutrients, can enhance maize cob size and yield. On the other hand, B deficiency in maize can result in barren cobs attributed to nonreceptive silks, which is particularly important for the female parent in seed production [21]. Understanding the molecular and cellular consequences of B deficiency is challenging due to limited availability of B imaging techniques [44]. However, it has been shown that B deficiency can cause severe developmental defects and sterility in maize, indicating its importance for plant growth and reproduction [19]. Although there were significant effects of growing season and genotype by environment interaction, positive and moderate correlations were found between B status in plants and grain yield [45]. Overall, while B deficiency has impact on maize cob development and overall plant growth. B has a significant effect on the number of kernels in maize. In a field experiment conducted by Kumar et al., [14] the treatment B3 (100 ppm) + Si3 (700 ppm) resulted in a higher number of grains per cob compared to other treatments. Another study by Nautiyal and Srivastava [46] found that the growth of maize kernels cultured in vitro was enhanced with the supply of B, leading to an increase in the number of kernels. Lordkaew et al. [22] observed that maize plants subjected to B deficiency had multiple but small and abnormal ears with a reduced number of grains, while plants with sufficient B produced a higher number of grains per ear. Additionally, an experiment using radioactive carbon-11 found that increasing levels of B led to increased 11CO2 fixation and allocation belowground, which could potentially affect kernel number [40]. Furthermore, in a wire house experiment, the application of B at a rate of 0.6 kg/ha increased grain yield by 27% in maize hybrids, which suggests a potential in-crease in kernel number [25]. Overall, these findings suggest that B application can have a positive impact on the kernel numbers of maize. Therefore, it can be concluded that B plays a crucial role in determining the number of kernels in maize. On another hand, B has been found to have an impact on the seed weight of maize. In one study, the application of B at a dose of 1.74 kg/ha resulted in the highest 1000-grain weight [9]. Another study found that the treatment with B at a concentration of 0.3% significantly increased the seed index of maize compared to the control treatment [47,48]. Additionally, the same study reported that the application of B at a dose of 0.6 kg/ha increased grain yield by 27% in both maize hybrids tested [35]. These findings suggest that B can positively influence the seed weight of maize, leading to improved grain yield. Adequate B in plant nutrition is critical for achieving high yield and quality of crops. The demand for B is greater during the reproductive phases, compared to the vegetative growth phase. The reproductive phase is a critical moment and sensitive to nutrient deficiency. Boron deficiency can lead to symptoms such as tiny, shriveled anthers that were empty of pollen and had lengthwise streaks of white to transparent color. Deficiency can also produce small or abnormal ears with very short silk small tassels with some of their branches emerging dead that are multiple and abnormally shaped. Plants subjected to B deficiency showed symptoms such as narrow white to transparent streaks on leaves, abnormal ears with short silk, and small, shriveled anthers devoid of pollen [22]. The deficiency also resulted in a de-crease in grain yield, with B0 plants producing only 0.4 grain ear compared to 410 grains ear in B20 plants [5]. The silk of the maize plant was found to be more sensitive to B deficiency compared to tassels and pollen [49]. Additionally, loss-of-function mutations of the tls1 gene, which is involved in B transport, led to the loss of reproductive structures in maize [44]. The rescue of the tls1 mutant phenotype with B supplementation was enhanced when plants were grown under specific lighting conditions [20].

3. CONCLUSION

In conclusion, this comprehensive review highlights the multifaceted role of boron (B) in maize cultivation, emphasizing its global significance, economic impacts, deficiency symptoms, effects on growth and development, factors affecting availability in soil, and various application methods. The implications of this study extend beyond agronomy, touching upon food security, economic sustainability, and environmental stewardship. Firstly, maize's status as a staple crop in many regions underscores the importance of addressing boron deficiency to ensure optimal yield and quality, particularly in low and lower-middle-income countries where maize plays a vital role in food security. Economic analyses emphasize the significant yield losses associated with B deficiency, urging for strategic management practices to mitigate these impacts and promote agricultural sustainability. Understanding the symptoms of B deficiency in maize is crucial for early detection and intervention, thereby safeguarding crop productivity. Moreover, insights into the physiological effects of B deficiency on maize plants, such as disrupted root growth and reproductive abnormalities, provide a basis for targeted management strategies. Factors affecting B availability in soil highlight the complexity of nutrient dynamics and underscore the need for tailored soil management practices to optimize B uptake by maize plants. Furthermore, the various methods of B application offer flexibility to farmers, each with its own advantages depending on factors like soil characteristics, crop stage, and resource availability. Moving forward, future research directions could explore the long-term effects of boron application on maize productivity and soil health, considering interactions with other nutrients and environmental factors. Additionally, optimizing application methods to enhance B efficiency and minimize environmental impact warrants further investigation. Longitudinal studies tracking B dynamics in soil-plant systems could provide valuable insights into sustainable nutrient management strategies. Overall, this synthesis underscores the importance of boron in maize cultivation and sets the stage for continued research aimed at enhancing agricultural productivity, economic resilience, and food security in maize-growing regions worldwide.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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