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Investigating Approaches for Optimizing Agricultural Yield: A Comprehensive Review of the Crucial Role of Micronutrients in Enhancing Plant Growth and Maximizing Production.

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ABSTRACT

Crop requires proper plant nutrition; one of the most important factors governing plant growth and development is the integrated supply of micronutrients and macronutrients in adequate amounts and appropriate proportions; although micronutrients are required in minute quantities, they play an important role in plant growth. Micronutrients must be used wisely in crop production to ensure the optimum output of high-quality products. Plant metabolism, nutrition management, chlorophyll synthesis, reproductive growth, flower retention, and fruit and seed development are all performed by micronutrients. Boron, chlorine, copper, iron, zinc, manganese, molybdenum, and nickel are micronutrients that are required by all higher plants. Chlorine, copper, iron, and manganese are engaged in diverse photosynthetic activities, whereas zinc, copper, iron, and manganese are involved in various metabolic processes. Molybdenum is exclusively found in nitrate reductase. Boron is related with glucose metabolism, plant reproduction, photosynthesis, and enzymatic activity. The review focuses on the primary roles of micronutrients in crop development and gives an overview of recent research discoveries linked to the role of micronutrients in plants, helping to improve knowledge of their importance.

Keywords- Zinc, Boron, Iron, Copper, Manganese, Molybdenum, Chlorine, Nickle, Absorption, Uptake, Function, Deficiency

I. INTRODUCTION

The discovery of micronutrients in plants is a relatively recent development in the history of science. In the 1860s, the German chemist Justus von Liebig discovered that plants also require small quantities of other trace elements, such as copper, zinc, and manganese, to grow and develop properly, he coined the term "micronutrients" to describe these essential elements, which are needed in much smaller amounts than the primary macronutrients like nitrogen, phosphorus, and potassium (Monib, A. W., et al. 2023, Sands, D. C., et al. 2009). Before the 19th century, the study of plant nutrition was primarily concerned with the roles of water, carbon dioxide, and minerals in plant growth (Antonkiewicz, J., & Łabętowicz, J. 2016). However, it was eventually discovered that plants require small quantities of certain trace elements to survive and thrive, which are now known as micronutrients (Paungfoo-Lonhienne, C., et al. 2012). The first micronutrient to be identified was iron (Akabas, S. R., & Dolins, K. R. 2005), in the 17th century, scientists observed that plants grown in soil rich in iron produced healthier leaves and stems than those grown in soil lacking the mineral (Chen, Y., & Aviad, T. 1990). However, it was not until the 19th century that iron was recognized as an essential nutrient for plant growth. In the early 20th century, researchers began to investigate the effects of different micronutrients on plant growth and development (Rattan, R. K., et al. 2009), they discovered that certain micronutrients, such as boron and molybdenum, are essential for the proper functioning of enzymes involved in plant metabolism (Loneragan, J. F. 1997), other micronutrients, such as cobalt and nickel, are involved in the synthesis of various plant compounds, including chlorophyll and vitamin B12 (Roychoudhury, A., & Chakraborty, S. 2022). As research into plant nutrition continued, scientists began to develop techniques for testing soil and plant tissues for their nutrient content (Jones Jr, J. B. 1997), this allowed farmers and gardeners to better understand the nutrient requirements of different crops and adjust their fertilization practices accordingly (Çakmak, İ., et al. 1999). Today, our understanding of plant micronutrients continues to evolve, as researchers discover new roles for these essential elements in plant growth and development. By ensuring that plants receive adequate amounts of all essential micronutrients, we can help to improve crop yields and promote healthy plant growth.

Micronutrients, essential for healthy growth and reproduction of plants and animals, are trace elements (Shukla, A. K., et al. 2018). The essential trace elements for plants are: B, Cl, Cu, Fe, Mn, Mo, Ni, and Zn. Co is only essential for bacterial nitrogen fixation in leguminous plants, while Si, Na, Se, Va, and Al are beneficial elements (Niazi, P., et al. 2023, Alloway, B. J. 2008). For animals, the essential trace elements are: Co, Cu, Cr, F, I, Fe, Mn, Mo, Se, and Zn. A micronutrient must meet three criteria to be essential: the organism cannot grow and reproduce normally without the element, its action must be specific, and it cannot be replaced by another element (Brown, P. H., et al. 2022). In geochemistry, trace elements occur in rocks and soils in small amounts, but in living organisms, they are present in even lower concentrations (He, Z. L., et al. 2005). The main organic compounds in plants and animals are C, H, O, and N. K occurs in similar concentrations to N, while P, Ca, Mg, Na, and Cl are in intermediate concentrations (Whitehead, D. C. 2000), meeting the micronutrient requirements of crops is important for satisfactory yields and quality products. However, excessive concentrations of the same elements can lead to toxicity (Hodges, S. C. 2010). Crop yields were lower in the past due to well-adapted cultivars and fewer fertilisers, intensification of farming practices led to an increased demand for micronutrients by crops and more instances of micronutrient deficiencies, differences in crop varieties can also affect the efficiency of their micronutrient uptake (Dhandapani, M., et al. 2023, Pretty, J., & Bharucha, Z. P. 2014, Jacobsen, S. E., et al. 2013). Each micronutrient has a specific role to play in plant growth and development (Shrivastav, P., et al. 2020, for example, iron is essential for the formation of chlorophyll, the green pigment that is responsible for photosynthesis. Manganese is involved in the synthesis of proteins and enzymes, while zinc is required for the development of new plant tissues (Hänsch, R., & Mendel, R. R. 2009). Boron is essential for cell wall formation, and molybdenum is required for nitrogen fixation (Naqib, S. A., & Jahan, M. S. 2017).

Micronutrient deficiencies can have a significant impact on plant growth and productivity (Egamberdiyeva, D. 2007), for example, a boron deficiency can lead to brittle and distorted plant growth, while a copper deficiency can cause the leaves to become chlorotic and stunted (Neelakantan, V., & Mehta, B. V. 1961). Iron deficiencies can cause the leaves to turn yellow, a condition known as chlorosis, while a lack of zinc can lead to reduced fruit set and poor seed quality (Uchida, R. 2000). To ensure that plants receive all the micronutrients they need, it is essential to have a good understanding of soil and plant tissue nutrient levels (Malvi, U. R. 2011), farmers and gardeners can use soil tests to determine the nutrient content of their soil and adjust their fertilization practices accordingly (Sultana, J., et al. 2015). Plant tissue analysis can also be used to identify nutrient deficiencies and adjust fertilization practices (Smith, P. F. 1962).

II. IMPORTANCE, AND EFFECT OF ZINC

Zinc is essential for plant growth and development because it participates in vital cell activities such as protein metabolism, gene expression, and bio-membrane integrity (Ozturk, H., et al. 2023). It promotes starch formation, seed production, and seedling vigor. In sensitive crops such as tomato, potato, beans, and onion, zinc deficiency produces interveinal chlorosis, slowed development, and leaf clustering (rosette), (Sidhu, M. K., et al. 2019, Jeyakumar, P., & Balamohan, T. 2007). It also assists in the manufacture of hormones and carbohydrates, the structural integrity of ribosomes, enzymatic activity, and photosynthesis (Gamage, D., et al. 2018). Zinc shortage and excess both cause stunted growth, delayed blooming, decreased yield, toxicity, and root and leaf damage (McCauley, A., et al. 2009). Zinc is needed for chlorophyll production and enzyme activation, as well as food absorption and stress tolerance (Sofy, M. R., et al. 2020). Plants are subject to environmental stress when they are deficient, it is critical to maintain soil zinc balance for maximum plant health and growth (Hajiboland, R. 2012).

Zinc is an important mineral element for agriculture, as it is required for plant development, but excessive levels can be harmful (Noulas, C., et al. 2018), it is required for plant growth, development, and reproduction, as well as the formation of chlorophyll, which is required for photosynthesis (Tripathi, D. K., et al. 2015). Zinc treatment has been found in studies to improve plant growth and output (Abdelaziz, A. M., et al. 2022). For example, applying zinc with 2,4-D (3 ppm) as a foliar spray to onion plants enhanced bulb weight (73.9 g) and bulb output (45 t/ha). Similarly, foliar treatment of zinc at various concentrations was found to alter growth and production features in chilies, with 4 ml/l of Zn being the best quantity for attaining economical fruit output. Foliar zinc application at 250 ppm resulted in maximum plant height, total dry weight, number and fresh weight of fruits/plant, and yield in tomato plants; in potato plants, foliar zinc application at 30 ppm significantly increased the number of tubers/plant, average weight, length, diameter of tuber, tuber yield/plot, and tuber yield/hectare compared to control (El-Khateeb, M. A., et al. 2023, Ahmed, R., et al. 2023). Overall, while zinc is necessary for plant growth and development, it is important to ensure that plants receive an adequate quantity of zinc to avoid harmful consequences.

III. IMPORTANCE, AND EFFECT OF BORON

Boron is an important element for plant growth and development, it is involved in a variety of physiological and biochemical activities, including as cell division, sugar transport, cell wall construction, and pollen germination. Boron deficiency can cause stunted growth, irregular root and shoot development, decreased fertility, and poor fruit quality (Rasheed, M. K. 2009). By assisting in the synthesis of pectin, a complex polysaccharide and a fundamental component of the cell wall, the micronutrient is also essential for preserving the structural and functional integrity of the cell wall, this function is especially critical in tissues with rapid cell division and growth, such as the apical meristem (Blevins, D. G., & Lukaszewski, K. M. 1998, Padayachee, A., et al. 2017).

Boron is also in charge of regulating other important nutrients including calcium, magnesium, and potassium (Malvi, U. R. 2011), it aids in the movement of calcium across the cell membrane, which is required to keep the cell wall strong and stiff, Boron also assists in the metabolism of plant hormones such as auxins, cytokinins, and abscisic acid, all of which are important in plant growth and development (Gaspar, T., et al. 1996). Boron is essential for the growth of fruits and seeds, it aids in the production of the ovule and pollen tube, as well as fruit differentiation. Boron shortage during fruit development can cause irregular fruit growth, uneven ripening, cracking, and softening (Teskey, B. J. 2012, Sathya, S., et al. 2009). To promote maximum plant development and production, it is critical to ensure that plants receive enough quantities of boron (Brown, P. H., & Shelp, B. J. 1997). Boron is mostly found as borax, boric acid, and disodium Octaborate Tetrahydrate (Wester, R. C., et al. 1998, Smith, R. A., & McBroom, R. B. 2000).). Crops including cabbage, cauliflower, sugar beet, and potato are extremely vulnerable to boron shortage, which can result in low yields, poor fruit quality, and, ultimately, economic losses (Prusky, D. 2011).

Boron is a trace element that is needed for plant growth and development, since it is involved in metabolic activities such as cell wall production, cell division, and nucleic acid metabolism (Bolaños, L., et al. 2004). Boron deficiency can cause stunted growth, decreased fruit and seed yield, and poor crop quality. Excess boron, on the other hand, may be poisonous to plants, causing tissue damage (Khaliq, H., et al. 2018). Boron is also used in the creation of borosilicate glass, ceramics, and fertilizers, among other things, it's also utilized to make semiconductors and as neutron absorbers in nuclear reactors. Furthermore, research indicates that boron may have certain health advantages for humans, including improved bone health, cognitive function, and immunological function. More study is needed, however, to validate these effects and find the ideal boron supplementation dose (Adair, Rick. Boron. 2007), several research have been conducted to explore the impact of boron spraying on plant development and production. According to one study, applying boron at a rate of 1 kg/ha resulted in the maximum broccoli production of 512.3 g/plant. Another study discovered that applying boron at a rate of 2.5 kg/ha was enough to raise boron levels in the soil. Boron treatment at a rate of 3 kg/ha resulted in the greatest seed production of 1769.11 kg/ha in carrot crops. Meanwhile, spraying 0.3% borax at 30 and 45 DAT resulted in the maximum total head output of 13.37 t/ha in broccoli. Furthermore, boron has been demonstrated to improve tomato plant blooming and fruiting, with a rate of 2 kg/ha boosting the number of flower clusters per plant, fruit set percentage, total yield, fruit weight loss, and total soluble solids. Furthermore, 0.5% boron treatment boosted onion growth, production, and quality, while another study found that boron at a rate of 2.0 kg B/ha had a beneficial effect on broccoli output and quality. Finally, boron foliar treatment at 120 and 150 ppm in sugar beet increased root output, characteristics, and the percentage of white sugar content (Aly, E. F. A., et al. 2020).

3.1. Combine Effect of Boron and Zinc

Several studies have demonstrated that applying zinc and boron to plants can improve their growth, production, and quality. (Roubin, G. S., et al. 2001) discovered that supplementing tomato plants with these micronutrients boosted the amount of ripe fruits per plant. (Ramana, K. V., & Srivastava, S. K. (2010) observed that foliar ZnSo4 and boric acid spray enhanced TSS levels in garlic. According to (Salam, O. E. A., et al. 2011), combining boron and zinc resulted in the maximum pulp weight, dry matter content, ascorbic acid content, lycopene content, and chlorophyll content in tomato. Similarly, (Jain, M., et al. 2013) discovered that combining zinc and boron boosted cauliflower plant height, number of leaves per plant, biological yield, curd weight, and marketable production. (Arnold, V. I., et al. 2013) investigated the interaction impact of these two micronutrients on the yield of dry and ripe chili per plant, finding that the application of Zn, B @ 3.91:1.70 kg/ha resulted in the maximum output.

(Abdul Karim, A., et al. 2014) investigated the influence of zinc and boron on broccoli growth, yield, and quality and discovered that administering these micronutrients had a substantial effect on the aforementioned metrics. According to, 0.5% zinc sulphate foliar spray resulted in highest plant height, number of leaves per plant, fresh leaf weight, fresh bulb weight, bulb yield per plot, and bulb production per hectare. According to (Hashem, H. E., et al. 2017), the interaction of boron and zinc enhanced tomato plant height, number of primary and secondary branches, number of leaves per plant, and number of fruits per plant. Overall, these studies show that zinc and boron are critical micronutrients that can boost plant growth, production, and quality. Furthermore, (Adrees, M., et al. 2015) reported that foliar application of ZnSo4 @12.5 ppm + H3Bo3 @12.5 ppm resulted in maximum plant height, leaf area, fruit length, fruit diameter, number of leaves, number of fruits, yield, and early flowering in tomato with the least number of diseased infested plants. Finally, (Ahmadi Mansourabad, M., et al. 2016) discovered that applying micronutrients (iron, zinc, and silicon) at a rate of 5mg/kg of soil reduced the number of galls per gram of root and increased cucumber shoot dry and fresh weights and fruit output.

IV. IMPORTANCE, AND EFFECT OF IRON

Iron is a micronutrient that plants require for regular development and function, as well as for a variety of metabolic activities. It assists in the absorption of other elements, including the creation of porphyrin molecules such as cytochrome, hemes, hematin, ferrichrome, and leg hemoglobin, and functions as a catalyst in the synthesis of chlorophyll, these chemicals participate in oxidation-reduction processes in respiration and photosynthesis, as well as DNA synthesis, protein synthesis, and nitrate and sulfate reduction. Iron is also a component of numerous enzymes and triggers several metabolic processes (Naser, M. N. 2000).

Iron is abundant in vegetable crops such as tomatoes, onions, carrots, and spinach, and a lack of it can cause interveinal chlorosis of young leaves and twig dieback, as well as yellowing foliage due to low levels of chlorophyll in extreme cases. Iron shortage is particularly troublesome in alkaline soils where iron availability is restricted, and it can be treated with iron sulfate or chelated iron. Iron may be obtained from ferrous sulfate ($FeSO_4.7H_2O$, 20%) and Fe-EDTA chelate (12% iron) (Sidhu, M. K., Raturi, H. C., et al. 2019).

Plants must be given with enough levels of iron, either through fertilizer or by selecting acceptable soil types for specific crops, to guarantee maximum development and productivity. Iron absorption in plants is a complicated process that is influenced by a variety of factors including soil pH, root exudates, and the presence of other minerals in the soil. Finally, iron is needed for plant growth and development since it is involved in the creation of chlorophyll, enzyme production, and gene expression control (Havlin, J. L. 2020). The nutritional absorption and protein percentage of seeds are significantly affected by iron treatment (Salih, H. O. 2013). Iron and manganese, for example, boost tuber output, mineral matter, carbohydrate buildup, and moisture content in potatoes. When compared to other treatments, applying approved levels of Ca, S, and Fe to chili considerably boosted yield. Iron concentrations of 0.6 mg/L were shown to be ideal for tomato development, leading in high manganese absorption, chlorophyll content, and total iron uptake. Iron is a micronutrient that is needed for plant growth and development. It is involved in the synthesis of chlorophyll, the generation of enzymes, the creation of energy, the control of gene expression, and the resistance to illness. Excess iron, on the other hand, can cause toxicity and damage to cellular membranes. As a result, maintaining an iron balance in the soil is crucial for guaranteeing maximum plant development and production (Rout, G. R., & Sahoo, S. 2015).

4.1. Combine Effect of Iron, Boron, and Zinc

Micronutrients such as iron, boron, and zinc can have a substantial influence on plant development and production. Chlorophyll synthesis, enzyme generation, energy production, gene expression control, and disease resistance all require iron. Excess iron, on the other hand, can be harmful, making it critical to maintain a balance in the soil. According to research, adding iron and manganese to potatoes can boost yield, mineral matter, carbohydrate accumulation, and moisture content, whereas chili plants benefit from Ca, S, and Fe recommendations. An ideal growth dosage of 0.6 mg/L of iron was discovered to boost manganese absorption, chlorophyll content, and total iron intake in tomatoes (Aref, F. 2012, Salih, H. O. 2013, Treder, W., et al. 2022, Niazi, P., et al. 2023).

Boron is also necessary for metabolic activities such as cell wall production, cell division, and nucleic acid processing, but an excess of it can be hazardous (Soetan, K. O., et al. 2010). Boron treatment has been shown in studies to boost plant production and quality, with rates changing by crop type. In tomato plants, for example, boron administration enhanced the number of flower clusters, fruit set %, total yield, and total soluble solids. Zinc is also required for plant growth and reproduction, but too much can be harmful. Zinc has been demonstrated to boost plant output in a variety of crops, including onion, chilies, tomato, and potato. To avoid detrimental impacts on development and output, plants must be given an adequate quantity of zinc, table 1, (Sadeghzadeh, B. 2013).

V. IMPORTANCE, AND EFFECT OF COPPER

Copper is a necessary nutrient for plants, regulating several biochemical events and playing an important role in a variety of metabolic and physiological processes (Sharma, A., et al. 2020). Copper, as a stable cofactor of enzymes and proteins, promotes iron usage during chlorophyll production and has an indirect effect on nodule growth (Broadley, M., et al. 2012). Copper shortage can result in stunted development, deformed younger leaves, and probable apical meristem necrosis, as well as yellowing of young leaves, curled tips, ragged leaf margins, and withering plant tops (Rajendran, C., et al. 2009). Copper is thus essential for good plant development and health, as evidenced by tomato tests (Sinisi, V., et al. 2018).

Copper is essential for plant growth and development, since it regulates several biochemical reactions as a stable cofactor of enzymes and proteins. Copper sulfate ($CuSO_4$) applied by soil or foliar spray can improve yield in potato and tomato plants, with foliar spray being more effective (Lamichhane, J. R., et al. 2018). Copper at 100 ppm has been shown to dramatically boost fruit yield per plant in tomatoes. Furthermore, copper can improve nutrient absorption in plants, with drip irrigation improving the uptake of major and micronutrients such nitrogen, phosphorus, potassium, zinc, iron, and copper. Copper is a vital component for plants in general (Kumar, V., et al. 2021).

5.1. Co- Importance, and Effect of Manganese, and Molybdenum

Manganese is required for plant development and growth. It activates photosynthesis and respiration enzymes, promotes germination and maturity, and increases phosphorus (P) and calcium availability (Ca). Manganese promotes root growth, fruit development, and disease resistance, as well as assisting with iron transport inside the plant, although plentiful in acid soils, it becomes less available in high-pH calcareous soils (Uchida, R. 2000). A lack of manganese causes chlorotic patches to turn light green or dull yellowish in hue (Rajendran, C., et al. 2009). Manganese is particularly beneficial to crops such as dry edible beans, cucumbers, lettuce, onions, peas, potatoes, and radishes (Nonnecke, I. L. 1989).

To investigate the influence of manganese concentrations in the culture medium on plant development, tomato cells in suspension culture were employed to determine biomass output, nutritional content, cell division, and viability. The study discovered that cells grown with Mn levels of 0.002 and 0.1 mM produced the most biomass and dry weight when compared to cells grown with 0 or 0.2 mM. In another trial, 4kg Zn + 1kg Mn/ha resulted in the highest plant height, number of leaves per plant, and quantity and weight of tubers, whereas the control resulted in the lowest results. Increased Mn concentrations in the growing medium (5, 25, and 50 mg dm^{-3}) were found to significantly increase Mn concentration, biomass accumulation, reactive oxygen species (ROS) levels, antioxidative enzyme activity, and phenolic compound content in lettuce leaves, with no significant changes in potassium, calcium, or magnesium concentrations. Manganese has been found to play an important role in plant growth and development by activating photosynthesis and respiration enzymes, encouraging germination and maturity, and increasing phosphorus (P) and calcium availability (Ca). Manganese also promotes root growth, fruit development, and disease resistance, as well as assisting with iron transport throughout the plant. Manganese has been shown in studies to improve biomass output, nutritional content, cell division, and viability in plants, as well as boost tuber yield in crops such as tomatoes and potatoes (Arnon, D. I., & Stout, P. R. 1939, Kaiser, B. N., et al. 2005, Banerjee, P., et al. 2021, Latha, K., & Dawson, J. 2023).

Furthermore, sufficient molybdenum levels influence carotenoid synthesis in plants. Molybdenum deficiency, on the other hand, can cause reduced plant development as well as leaf chlorosis and necrosis. Interestingly, because molybdenum is essential for nitrogen absorption in plants, the symptoms of molybdenum insufficiency are identical to those of nitrogen deficit. Molybdenum insufficiency is frequent in nitrogen-fixing legumes such as beans, peas, and clovers, which need high quantities of molybdenum to fix nitrogen. As a result, it is critical to ensure that plants have adequate molybdenum levels to sustain their growth and development. Overall, molybdenum is an essential element for plants, and a lack of it can have serious consequences for plant health and production (Feng, J., et al. 2023).

VI. IMPORTANCE, AND EFFECT OF CHLORINE

Chlorine is a necessary micronutrient for plant growth and development, serving a variety of activities, it is a critical component of the enzyme that catalyzes the water-splitting activity in photosystem II, which makes it essential for photosynthesis. Furthermore, chlorine assists in the control of stomatal openings and boosts cell osmotic potential, both of which are required for shoot apex and root development (Cakmak, I., et al. 2023) Apart from its role in photosynthesis, chlorine is frequently utilized in agriculture as a sanitizer due to its inexpensive cost in maintaining fruit quality. It preserves their look, texture, flavor, soluble solids content, acidity, pH, and shelf life while also inhibiting microbial development, which is critical for disease prevention (Niazi, P., et al. 2023). Chlorine is a multipurpose element that acts as a sanitizer as well as an important micronutrient for many crops. It is important not only for fruit quality, but also for photosynthesis and stimulating shoot apex and root growth, making it a vital component for healthy plant growth and development (Dhiman, S., et al. 2023). Although chlorine shortage in plants is uncommon, it can cause chlorosis of younger leaves and overall plant withering. Certain vegetable crops, such as potatoes and beans, are more vulnerable to a lack of chlorine than others. However, because chlorine can be found in the environment and precipitation, plants usually have enough of it to suit their demands.

Chlorine, an important micronutrient for plants, is required for their growth and development. It contributes to photosynthesis as a component of the enzyme that catalyzes the water-splitting activity in photosystem II, aids in stomatal control, and boosts cell osmotic potential, which is required for shoot apex and root development (Chen, W., et al. 2010). However, chlorine may be harmful to plants, especially when present in high amounts. Although chlorine is commonly used as a sanitizer in agriculture to limit microbial development and maintain fruit quality, excessive quantities of chlorine can be hazardous to plants. Chlorosis of younger leaves and general plant withering are frequent indications of chlorine poisoning, and specific vegetable crops, such as potatoes and beans, are especially susceptible (Alloway, B. J. 2008).

While chlorine is required for plant development at low levels, its concentration and use in agriculture should be carefully addressed to avoid harmful effects on plant health and fruit quality. It is critical for optimal plant growth and development to weigh the advantages and hazards of chlorine use (Martínez-Ballesta, M. C., et al. 2010). Several studies have been conducted to assess the effectiveness of chlorine treatment in increasing the quality and shelf life of vegetables. According to one study, treatment with 100 ppm chlorine successfully decreased microbial load in onions without generating major quality losses. Another study looked at the effect of washing tomato fruits with a 200 ppm chlorine solution before storage, which resulted in a slower decay rate and a longer shelf life when compared to untreated fruits (Glowacz, M., et al. 2015).

A different study focused on green chili, which was pre-treated with chlorine water and packaged in a 0.3% perforated polypropylene packet, resulting in a significant reduction in weight loss and rotting/shriveling, as well as the retention of vitamin C, carotene, and moisture content, extending the shelf life to up to 10 days at ambient conditions. Increasing the chloride concentration in nutrient solutions from 90 to 120 mg Cl-dm-3 was found to increase chlorine content but decrease nitrogen, ascorbic acid, reducing sugars, and dry matter content in tomato fruits, with no effect on nitrate and nitrite, acidity, or carotene content. Furthermore, increasing chloride concentration in nutritional solutions can lower tomato fruit nitrogen, ascorbic acid, reducing sugars, and dry matter content while having no effect on nitrate and nitrite, acidity, or carotene content (Neocleous, D., et al. 2021).

VII. IMPORTANCE, AND EFFECT OF NICKEL

Nickel is an important micronutrient for plants that performs a variety of important tasks, including the activation of urease, which regulates senescence and is vital for nitrogen metabolism. Nickel is also essential for iron absorption and can function as a cofactor for some enzymes in place of zinc and iron. Nickel deficiency, on the other hand, can cause leaf tip necrosis in nitrogen-fixing plants and impair nitrogen fixation effectiveness in leguminous vegetable crops by delaying nodulation. Nickel is very important during the reproductive period of cowpea. As a result, maintaining an appropriate supply of nickel is critical for optimal plant growth and development (Anke, M., et al. 1995, Harasim, P., & Filipek, T. 2015, Brown, P. H. 2016, Dotaniya, M. L., & Nagar, M. C. 2023).

Nickel is necessary for plant growth and development, but in greater amounts it can be harmful. The ideal concentration for growth and yield is about 30 mg/kg soil, which promotes plant height, branch number, leaf area, root length, fruit quality, auxin and gibberellin content, and increases nitrogen, phosphorus, and potassium in tomato fruits. High nickel concentrations (>50 M) on the other hand, can have a deleterious impact on plant biomass, photosynthetic pigments, iron metabolism, catalase, peroxidase activity, and chlorophyll content in leaves and stems. When exposed to high nickel levels (1.0 and 10.0 ppm), lettuce exhibits apparent toxicity signs such as wilting, chlorosis, browning of root tips, damaged roots, and reduced chlorophyll a and b contents. Similarly, larger nickel dosages (30-40 mg Ni/kg soil) reduce tomato plant growth and chlorophyll content, as well as the dry weight of roots, shoots, leaves, fruit output, and overall plant development. In one study, 30 mg Ni/kg soil produced the highest plant height, number of branches, leaf area, root length, fruit quality, auxins, and gibberellins contents, and all nickel concentrations (15, 30, 45, and 60 ppm) promoted nitrogen, phosphorus, and potassium content in tomato fruits when compared to the control group. Plant exposure to Ni > 50 M, on the other hand, reduced biomass, photosynthetic pigments, Fe concentration, catalase and peroxidase activity, and chlorophyll content, as well as interfering with iron metabolism in eggplant (, Zhang, Z., et al. 2023, Oláh, V., et al. 2023). Another study used different nickel doses (10, 20, 30, and 40 mg Ni/kg soil) on tomato plants, with lower doses having no effect on growth but higher doses (30-40 mg Ni/kg soil) reducing chlorophyll content, dry weight of roots, shoots, leaves, fruit production, and overall plant growth; thus, nickel

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concentration and usage must be carefully considered to ensure optimal plant growth and fruit quality while avoiding toxicity (Brown, P. H., et al. 1987, Bhalerao, Satish A., et al. 2015, Ahmad, M. S. A., & Ashraf, M. 2011, Chen, C., et al. 2009).

VIII. COMBINE EFFECT OF MICRONUTRIENTS

Different application strategies can demonstrate the considerable influence of micronutrients on plant development and output. Foliar treatment of micronutrients such as B, Zn, Cu, Fe, and Mn has been proven to improve plant height, number of branches/plant, fruit length, fruit diameter, fruit yield/ha, and marketable fruit yield/ha in crops such as tomato and cauliflower, a 10 kg/ha soil treatment of micronutrients such as ZnSO4, borax, and CuSO4 can improve onion plant height, number of leaves, bulb weight, total yield, and TSS (Badran, F. S., et al. 2017, the influence of varying zinc, boron, and manganese concentrations on okra production indicated that the maximum yield was obtained when the plants were cultivated in soil with the highest amount of zinc. Boron and manganese have varied impacts on tomato fruit production and anti-oxidative content based on concentration (Rahman, M. H., et al. 2020), the effect of several treatment combinations on onion growth and yield was substantial. Cauliflower performed best when treated with certain combinations of treatments, including boron and sodium molybdate (Farooq, M., et al. 2012, Pankaj, P., et al. 2018).

Foliar application of micronutrients such as RDF + B, Zn, Cu, Fe, and Mn significantly improved plant height, number of branches per plant, and fruit yield/ha. The usage of varying micronutrient doses also enhanced the morphological properties of spinach (Sidhu, M. K., et al. 2019). The application of ZnSo4, Borax, and CuSo4 at a rate of 10kg/ha in soil resulted in the maximum plant height, number of leaves, bulb weight, total yield, and TSS in onion, while the control had the lowest values. Similarly, foliar sprays of micronutrients such as General grade-1 (Fe-2.0, Mn-0.5, Zn-4.0, Cu-0.3, and B-0.5) + T1 (Ammonium molybdate) boosted cauliflower plant growth and production (ZAMAN, M. S. 2008). While some nutrients, such as aluminum, can stimulate growth in a variety of plants, their essentiality has only been demonstrated in a few species or particular metabolic processes that are not always required (Brown, P. H., et al. 2022). Note: The optimum percentage values given in the table 2 refer to the ideal concentration of the respective micronutrient in plant tissues; these values may vary depending on plant species and growth stage; the table is not exhaustive, and the effects of micronutrient combinations may vary depending on plant species, soil type, and environmental conditions.

IX. GENERAL EFFECT OF MICRONUTRIENTS

Micronutrients are essential for plant growth because they aid in a variety of physiological and biochemical processes. They can boost plant growth and increase macronutrient absorption and utilization, resulting in better yields. Micronutrient deficiencies can result in stunted growth, lower yields, and susceptibility to pests and illnesses. Some micronutrients are required in minute amounts yet are critical for plant growth, and their use can increase crop quality (Waraich, E. A., et al. 2011). Al treatment enhanced the growth and absorption of N, P, and K in the AI-tolerant plant, particularly P uptake, whereas Al application inhibited the growth and uptake of these nutrients in the AI-sensitive plant (Osaki, M., et al. 1997). A cobalt concentration of 7.5 ppm considerably boosted sugar beet growth, root production, mineral composition, sugar yield, and percentages of protein, carbohydrate, vitamin C, sucrose, and glucose (Gad, N., & Kandil, H. 2009). The addition of a 0-20 mg/l NH4VO3 nutritional solution increased stem length, dry weight of leaves, stem, and roots. In Chinese green mustard and tomato plants, increasing the vanadium content (40-80 mg/l) reduced stem length, root length, and fruit fresh weight (Sidhu, M. K., et al. 2019). Tomato plants irrigated with a silicon-enriched fertilizer solution had considerably more total fruit (15.98 kg/plant) and had leaves that contained more silicon and less manganese and zinc than the control (Jarosz, Z. 2014). Germination is feasible up to the greatest NaCl salt concentration (16 g/l) in carrot. However, when concentration increases, germination and germination speed decrease (Basma, K., et al. 2014). Silicon at 50 and 100 mg/L considerably enhanced tomato fruit size, hardness, titrable acidity, and disease resistance against anthracnose (Jayawardana, R. K., et al. 2016).

In comparison to non-Si treated plants, 1.5 mM silicic acid reduced Mn toxicity and boosted growth and biomass production in cucumber (Liang, Y., et al. 2015). In cucumber, foliar spraying (50, 100, 200 mg/l) or soil soaking (500, 1000, and 2000 mg/l) produced the maximum fruit firmness, TSS, ascorbic acid, and fruit production. In comparison to untreated plants, Si-treated plants had more Si in the leaves/fruits and more phosphorus and potassium in the leaves (Pichyangkura, R., & Chadchawan, S. 2015). 5 M vanadium boosted plant growth, stimulated floral bud development, blooming, chlorophyll concentration, amino acids, and nitrogen, phosphorus, potassium, calcium, magnesium, copper, manganese, and boron concentrations in pepper stems (Singh, J., et al. 2013). In comparison to the control, 0.04% sodium azide increased the number of leaves, plant height, fresh weight, and dry weight. However, increasing the sodium azide dosage had a negative effect on the germination percentage (%) of okra (Rasik, S., et al. 2022).

The table 1: Summarizing the deficiency, importance, percentages, role, and combined effect of Iron, Boron, and Zinc in plants

Nutrient	Deficiency Symptoms	Importance	Percentage of Dry Plant Tissue	Role in Plants	Combined Effect
Iron	Chlorosis of young leaves, and interveinal yellowing	Essential for photosynthesis, respiration, and nitrogen fixation	0.02-0.1%	Component of various enzymes and proteins, electron carrier	Boron deficiency can exacerbate iron deficiency; Zinc deficiency can interfere with iron uptake
Boron	Stunted root, and shoot growth, distorted leaves and fruit	Essential for cell wall formation, pollen tube growth, and carbohydrate transport	0.1-0.5 ppm	Structural component of cell walls, and enzyme cofactor	Zinc can partially compensate for boron deficiency
Zinc	Chlorosis of leaves, and stunted growth	Essential for enzyme activity, hormone regulation, and stress response	20-200 ppm	Enzyme cofactor, and regulates gene expression	Boron can partially compensate for zinc deficiency; Iron deficiency can interfere with zinc uptake

Table 2: Combined effects of different micronutrients on plant parts

Micronutrient	Function in Plants	Deficiency Symptoms	Plant Part Affected	Optimum Percentage
Iron	Required for chlorophyll synthesis and energy transfer	Chlorosis in young leaves	Leaves	0.3-3 ppm
Zinc	Necessary for protein synthesis, growth regulation, and stress tolerance	Stunted growth, chlorosis, and malformed leaves	Leaves and Stems	15-60 ppm
Manganese	Involved in photosynthesis, and enzyme activation	Interveinal chlorosis, and necrosis	Leaves	20-200 ppm
Boron	Required for cell wall formation, and pollen tube growth	Brittle leaves, stunted growth, and reduced fruit production	Leaves and Stems	20-100 ppm
Copper	Needed for photosynthesis, and reproductive growth	Chlorosis, wilting, dieback of stems, and leaves	Leaves and Stems	3-20 ppm
Molybdenum	Essential for nitrogen fixation, and enzyme activation	Yellowing of leaves	Leaves	0.1-1 ppm
Chlorine	Involved in osmoregulation, and photosynthesis	Wilting and chlorosis of leaves	Leaves	0.1-0.2% of dry weight
Nickel	Necessary for urease activity, and nitrogen metabolism	Inhibition of growth, and leaf distortion	Leaves	1-10 ppm

X. CONCLUSION

In the growth and development of crops, the role of micronutrients is indispensable, with the nutritional value of crops becoming a major concern, the application of micronutrients is of profound importance in sustaining soil health, enhancing crop productivity, and maintaining the quality of vegetables, the benefits of micronutrients include improving yield and quality, promoting earliness and fruit setting, increasing post-harvest life, and developing resistance to biotic and abiotic stresses. Micronutrients are vital for crop growth and development, yet often overlooked. They play a critical role in sustaining soil health, improving crop productivity and preserving the quality of vegetables. Micronutrients help plants in various physiological processes, such as photosynthesis and enzyme activation, and aid in resistance to biotic and abiotic stresses. The most common micronutrients required for crop growth are iron, manganese, zinc, copper, boron, molybdenum, and chlorine. By ensuring crops receive the necessary micronutrients, farmers can improve their yield, quality, and post-harvest life.

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