***Review Article***

**The role of micronutrients in sustainable production**

**Abstract**

Considering the world's expanding population, sustainable agriculture is becoming more and more important for maintaining environmental health and food security. Micronutrients like iron, zinc, manganese, and copper are among the essential elements of plant nutrition and are essential for improving crop yield, food quality, and plant health. Micronutrient deficiencies can result in severe decrease in agricultural productivity, increased susceptibility to diseases, and poor nutritional quality of food crops, with additional health consequences for humans, even though they are necessary in trace amounts. The physiological roles of micronutrients, their significance in plant systems, and the intricate relationships between them in the soil environment are all covered in this review. It looks at cutting-edge, environmentally friendly methods of managing micronutrients, such as integrated nutrient management, soil testing, biofortification, and precision agriculture technologies. We can improve soil fertility, boost crop resilience, and advance food security by deepening our understanding of micronutrient dynamics and putting best management practices into practice. This will ultimately support sustainable agricultural systems and the general economic viability of farmers around the world. To promote these methods and guarantee long-term agricultural sustainability, future studies and legislative assistance are crucial.

**Keywords: soil fertility, soil testing, micronutrients, sustainable agriculture, and deficiency**
**Introduction**
To guarantee food security, environmental health, and economic viability, sustainable agriculture is an essential strategy (Tilman *et al*., 2002). The demand for food production is rising along with the world's population, so it is critical to implement farming methods that increase productivity without endangering natural resources. Maintaining ideal soil health and plant nutrition is a crucial component of sustainable agriculture, as it is essential for long-term agricultural productivity and ecological balance.

Despite having a major influence on crop yield, plant health, and food quality, micronutrients are frequently disregarded as crucial elements of plant nutrition. Micronutrients are needed in trace amounts, in contrast to macronutrients like potassium (K), phosphorus (P), and nitrogen (N), which are needed in large quantities. Nonetheless, their existence is essential for plant stress tolerance, metabolic processes, and enzymatic activities (Alloway, 2008). Micronutrient imbalances or deficiencies can result in poor crop productivity, heightened disease susceptibility, and subpar food crop nutrition, all of which can have an impact on the health of people and animals.

In comparatively smaller amounts, plants absorb and use micronutrients such as boron (B), copper (Cu), chlorine (Cl), iron (Fe), zinc (Zn), manganese (Mn), and molybdenum (Mo) as vital nutrients. The growth, development, and metabolism of plants are significantly influenced by these micronutrients. Nevertheless, their deficiencies can cause several plant diseases, which can subsequently lower the amount and quality of food produced. As a result, research on the function of micronutrients in plants has sparked incredible interest and is a topic of great importance to scientists. Micronutrients are known to have a variety of functions, and a sufficient supply of them boosts plant growth and yield while shielding the plants from the negative effects of biotic and abiotic stressors (Fig. 1) (Tripathi *et al*., 2015).



Figure 1. Micronutrient responses to various biotic and abiotic stresses (Tripathi *et al*., 2015).

The role of soil is crucial in shaping the agro-system for sustainable productivity. The sustainability of fertility is contingent upon the soil's capacity to provide vital nutrients to the developing plants. Deficiencies in micronutrients significantly hinder the productivity, stability, and sustainability of soils (Bell and Dell, 2008). The deficiency of micronutrients can result from their insufficient levels or from soil conditions that hinder plant development. Improper nutrient management results in multiple nutrient deficiencies in Indian soils (Sharma, 2008). Furthermore, the ongoing disregard for micronutrient application and the neglect of organic manures are major factors contributing to the deficiency of micronutrients (Srivastava *et al*., 2017). Several steps can be taken to identify the deficiency of the nutrient in both plant and soil. Table 1 represents the several strategies followed for the identification of nutrient deficiency

Table 1. Possible steps to identify the nutrient deficiency

|  |  |
| --- | --- |
| Soil Testing | The soil sample is collected and analysed from an extensive area to ascertain its composition and nutrient levels. |
| Visual Deficiency Symptoms | **Symptoms resulting from nutrient deficiencies typically manifest on leaves, fruits, and the entire plant, identifiable by distinct characteristics.** |
| Plant Tissue Analysis | **This includes chemical analysis of plant leaves and other tissues to determine their nutrient composition.** |
| Rapid Tissue Test | **The growth and productivity of crops are influenced by various factors, among which the nutrient status of plant components, including leaves and stems, is crucial. To conduct a rapid tissue test for evaluating nutrient status, it is essential to collect various parts of the plant as indicator tissues, including the petiole, leaf lamina, leaf blade, and stem/midrib.** |

Sustainable micronutrient management encompasses a comprehensive strategy that incorporates soil health preservation, application of organic amendments, biofortification, and precision agriculture technologies. Recent research has underscored the significance of micronutrient enhancement in crops via biofortification strategies, aiding in the fight against global malnutrition while promoting agricultural sustainability (Bouis and Saltzman, 2017). The incorporation of organic farming methods, microbial inoculants, and precision fertilization has demonstrated potential in enhancing nutrient availability while reducing environmental harm (Easwaran *et al*., 2024).

This review examines the significance of micronutrients in sustainably cultivated produce, their physiological roles in plants, and the repercussions of their deficiencies. It also investigates innovative and sustainable approaches for managing micronutrients to augment soil fertility, bolster crop resilience, and support food security. Comprehending the importance of micronutrients and applying optimal management practices can greatly enhance sustainable agricultural systems, ensuring environmental preservation and economic success for farmers globally.

**Importance of Micronutrients in Plant Growth**

Micronutrients refer to a group of elements that are essential for plant growth and development but are required in much smaller quantities than macronutrients (nitrogen, phosphorus, and potassium). Micronutrients play a vital role in crop growth, crop productivity, soil fertility and human nutrition. Micronutrients, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl), are essential for various physiological and biochemical processes in plants. Micronutrients serve as co-factors in enzymatic reactions, play role in photosynthesis, and are essential for the synthesis of hormones and chlorophyll. Their deficiencies can lead to reduced yield and compromised quality (Marschner, 2012). The following are key functions of micronutrients:

* **Iron (Fe):** Essential for chlorophyll synthesis and electron transport in photosynthesis; deficiency leads to interveinal chlorosis in young leaves, reduced photosynthetic efficiency, and ultimately lower yields. Iron is also involved in respiration and nitrogen fixation in leguminous plants (Briat *et al*., 2015).
* **Manganese (Mn):** Plays a crucial role in enzyme activation, carbohydrate metabolism, and nitrogen assimilation. It is required for photosystem II function in photosynthesis, and its deficiency results in weak plant structures, delayed maturity, and reduced tolerance to abiotic stress (Broadley *et al*., 2012).
* **Zinc (Zn):** Involved in protein synthesis, auxin production, and enzyme activity. It also enhances plant tolerance to environmental stressors such as drought and heat. Zinc deficiency leads to leaf bronzing, shortened internodes, and impaired flower and fruit development (Alloway, 2008).
* **Copper (Cu):** Required for lignin synthesis, cell wall strengthening, and reproductive development. It participates in electron transport during photosynthesis and respiration. Copper deficiency results in wilting, increased susceptibility to fungal infections, and impaired reproductive growth (Zewide, 2021).
* **Boron (B):** Essential for cell wall integrity, sugar transport, pollen tube elongation, and seed formation. Deficiency causes brittle plant tissues, malformed fruit, and reduced seed viability. Boron also plays a role in calcium utilization, affecting overall plant structure (Shorrocks, 1997).
* **Molybdenum (Mo):** Integral to nitrogen metabolism and enzymatic reactions, molybdenum is essential for the activity of nitrate reductase and nitrogenase enzymes. Its deficiency impairs nitrogen fixation in legumes, leading to poor plant growth and lower protein content in food crops (Hansch and Mendel, 2009).
* **Chlorine (Cl):** Maintains osmotic balance, regulates stomatal function, and aids in photosynthesis. Chlorine deficiency is rare but can lead to reduced root development, delayed maturity, and lower disease resistance (White and Broadley, 2005).

**Importance of micronutrients in crop production**

“Micronutrients are known to increase quality and yield since most of them act as cofactors in various enzymes taking part in various metabolic activities of the plant like protein metabolism, carbohydrate metabolism, photosynthetic rate etc. Therefore, there will be increase in protein content, Total soluble solute and other quality parameters which results in improvement of the quality and other micronutrients like iron, important for chlorophyll formation, photosynthesis will also increase and thus increase in yield. In legumes, it influences N2-fixation because micronutrients like Fe and Mo are important constituent of nitrogenous enzymes which helps in leghaemoglobin formation (O2 scavenger)” (Rahman *et al*., 2020).

**Causes of micronutrient deficiencies**

* **Intensive cropping:** Intensive cropping practices, characterized by the continuous cultivation of crops without adequate nutrient replenishment, can lead to the depletion of essential micronutrients in the soil, adversely affecting long-term soil fertility and crop productivity (Fageria *et al.,* 2008).
* **Loss of top soil by erosion:** Environmental factors such as excessive rainfall and strong winds can lead to the leaching and erosion of micronutrients from the soil, ultimately resulting in nutrient deficiencies (Meena *et al*., 2017).
* **Use of marginal lands for crop production:** Use of poor soils which have less fertility for crop production (Nayyar, 1999).
* **Loss of micronutrients through leaching:** Excessive rainfall results in leaching of micronutrients in the deeper layers of soils, thus there is deficiency of micronutrients in the rhizosphere (Meena *et al*., 2017)
* **High demand of modern crop cultivars:** Modern high-yielding crop cultivars are bred to meet market demands for productivity and quality; however, these cultivars often have higher nutrient requirements, leading to accelerated depletion of micronutrients from the soil (Cakmak, 2008)

**Micronutrient Deficiency Scenario in Soils and Plants**

The micronutrient content in soil depends on various factors, including parent material, inherent soil properties such as pH and electrical conductivity (EC), the quality and quantity of calcium carbonate and soil organic matter, trace elements from manures and fertilizers, available macronutrient content, micronutrient interactions, and vegetation (Fageria *et al*., 2002; Alloway, 2008; Shukla *et al*., 2016). The leaching loss of micronutrients, soil liming, restricted application of manures, and excessive use of micronutrient fertilizers lacking additional micronutrient inputs exacerbate the depletion of available micronutrients in soils.

The total soil micronutrient content is determined by parent material and pedogenic processes. Indian soils exhibit a satisfactory level of total micronutrient content. Despite the relatively high total micronutrient content, deficiencies have frequently been observed in various crops, attributed to the low availability of accessible micronutrients (Singh 2008; Behera and Shukla, 2014; Shukla and Tiwari, 2016). Over 50% of soils exhibited zinc deficiency in states such as Goa (55.3%), Rajasthan (56.5%), Madhya Pradesh (57.1%), and Tamil Nadu (63.3%). Conversely, less than 10% of soils demonstrated zinc deficiency in states including Arunachal Pradesh, Uttarakhand, Tripura, Nagaland, Mizoram, Meghalaya, and Himachal Pradesh. Cu deficiency exceeded 5% in Haryana (5.1%), Rajasthan (9.2%), and Tamil Nadu (12.0%). Higher manganese deficiency has been reported in light-textured rice-growing soils, particularly within rice-wheat systems, in states such as Rajasthan (28.3%), Punjab (26.2%), Goa (16.9%), Uttar Pradesh (15.8%), and Chhattisgarh (14.8%). Between 35% and 60% of soils in states characterized by acidic conditions, such as Jharkhand, Odisha, Karnataka, Jammu and Kashmir, Himachal Pradesh, Manipur, Meghalaya, Mizoram, and West Bengal, exhibited boron deficiency. A Mn deficiency of 5–10% has been documented in the soils of states such as Bihar, Haryana, Himachal Pradesh, and Telangana (Shukla *et al*., 2018).

The optimal concentrations of micronutrients in plants are as follows: 100 mg kg−1 for Cl, 50 mg kg−1 for Mn, 100 mg kg−1 for Fe, 20 mg kg−1 for B, 20 mg kg−1 for Zn, 0.1 mg kg−1 for Mo, 0.1 mg kg−1 for Ni, and 6 mg kg−1 for Cu, based on dry matter.

The visual diagnosis of micronutrient disorders serves as a significant method for the rapid identification of plant health in relation to fertility, micronutrient availability, uptake, and the validation of soil or foliar test outcomes. Metabolic disturbances resulting from micronutrient deficiencies establish connections between the role of an element and the manifestation of specific developmental deficiencies in plants (Jatav *et al*., 2020).

**Micronutrient Status in Indian Soil**

**Iron (Fe):** Iron ranks second to aluminium in the hierarchy of abundant metals found in the soil. Plants absorb iron in the form of either Fe2+ (ferrous ion) or Fe3+ (ferric ion). Ferric iron compounds exhibit low solubility, and the conditions that promote the formation of these compounds diminish iron availability in the soil (Jatav *et al*., 2020). Sahu *et al*. (1990) performed a distribution study on the availability of Mn, Zn, Fe, and Cu in both subsurface and surface soils from eight soil groups in rice-growing regions of Odisha, noting that Fe, Mn, and Cu were sufficiently present in these soils. Nonetheless, a deficiency of available Zn extracted by DTPA (<0.6 ppm) was identified. Vijay Kumar *et al*. (1996) presented comprehensive reports on the reduction of micronutrient levels in the soils of Northern Telangana. The reports indicate that the soils of Northern Telangana exhibit low organic carbon levels and vary from low to high in cation exchange capacity (CEC). The concentrations of Fe, Cu, and Mn in the soils range from 19 to 59.9 mg kg−1, 1.01 to 5.19 mg kg−1, and 15 to 86 mg kg−1, respectively. The upper layer of soil possesses a higher concentration of nutrients compared to the subsurface layers. Chattopadhyaya *et al*. (1996) examined nine soil profiles from three districts in the Vindhyan scrap land region to assess the status of Zn, Cu, Fe, and Mn, finding that soils at higher elevations contained a greater concentration of micronutrients compared to those at lower altitudes. Sarkar *et al*. (2000) discovered elevated levels of DTPA-extractable Fe, Cu, Zn, and Mn in the surface layers of nearly all soil profiles in the Madhubani district of Bihar.

**Zinc (Zn):** The Zn2+ cation is the primary form accessible to plants. In soil, zinc exists as the divalent cation Zn2+ and can be found in forms such as water-soluble Zn2+, exchangeable Zn2+, and adsorbed Zn2+ on the surfaces of clay, organic matter, carbonates, and oxide minerals (Jatav *et al*., 2020). Sharma *et al*. (1996) examined the arid-zone soils of Punjab and found them to be alkaline yet deficient in micronutrient elements. Sen *et al*. (1997) noted that the available zinc content in the soils of Manipur varied from 0.2 to 1.4 mg kg−1 and diminished with depth. The valley soils exhibited significantly lower zinc content compared to the soils of the inter-hill valley and the hill. Singh *et al*. (1997) presented a report on the DTPA-extractable zinc content in the soils of rice fields in Meghalaya. The concentration of DTPA-Zn in the soils diminished with rising altitude. Sharma *et al*. (2003) examined soils in the semi-arid region of Rajasthan to assess micronutrient levels and the influence of soil properties on these levels. The study demonstrated that Zn, Fe, Cu, and Mn exhibited positive correlations with organic carbon and silt + clay, while showing a negative relationship with calcium carbonate content and pH. Talukdar *et al*. (2009) conducted a study on the DTPA-extractable micronutrient cations and their correlation with the physicochemical properties of soil in two agroecosystems of Golaghat district, Assam. The DTPA-extractable micronutrient cations exhibited a positive correlation with cation exchange capacity and organic carbon content, irrespective of the land-use pattern. They noted that all micronutrients exhibited a significant negative correlation with soil pH.

**Copper (Cu):** The prevalent forms of soil copper include: (i) ionic and complexed forms in the soil solution; (ii) bound to cation-exchange sites on clays and organic matter, retained electrostatically due to Coulombic forces; (iii) co-precipitated within soil oxide materials; and (iv) present in biological residues and living organisms (Jatav *et al*., 2020).

Sangwan and Singh (1993) investigated ten profiles of semi-arid soils in southern Haryana to evaluate the vertical distribution of Zn, Mn, Cu, and Fe in relation to depth and other significant soil characteristics. The distribution of Mn and Fe was influenced by pH and CaCO3 content, while clay and CEC regulated the availability of Cu. Jalali and Sharma (2002) examined the soils of an intermediate mid-hill region in Jammu and discovered that soils with low organic matter and high pH levels typically exhibited low concentrations of Zn, Cu, Fe, and Mn. Gupta *et al*. (2003) examined 24 profiles from six established series (Madhaiyapura, Palri, Taton, Bhangarh, Richarikala, and Bagwai) in Northern Madhya Pradesh to assess the DTPA-extractable micronutrient cations (Zn, Cu, Fe, and Mn) and their correlation with various soil properties. The analysis of soil series profiles revealed that the concentrations of zinc, iron, and manganese generally diminished with depth, whereas copper peaked in the layer between 15 and 60 cm before subsequently declining with depth. Sharma and Chaudhary (2007) investigated the vertical distribution of available micronutrient cations (Zn, Cu, Fe, and Mn) and their correlation with various properties across 32 profiles of 8 prospective soil series in the Mandhala watershed, representing the lower Shiwaliks of Solan district in Himachal Pradesh. The study indicated that the concentration of available Cu was elevated at the horizontal surface and diminished with depth. The concentration varied from 0.30 to 2.80 mg kg−1 across nearly all soil series.

**Manganese (Mn):** Manganese is recognized to exist in three valence states in the soil: (i) divalent manganese (Mn2+), which is present as an adsorbed cation or in the soil solution; (ii) trivalent manganese (Mn3+), which manifests as the highly reactive oxide Mn2O3; and (iii) tetravalent manganese (Mn4+), which is found as the very inert oxide MnO2. Manganese (Mn) concentration in soil solution markedly rises in acidic soils; the solubility of Mn2+ may reach levels that induce toxicity in sensitive species. The predominant form of manganese absorbed by plants is Mn2+(Jatav *et al*., 2020). Tripathi *et al*. (1994) examined the soils of Himachal Pradesh and noted that the distribution of available manganese did not exhibit a consistent trend with depth in the soil profile. An average concentration of 29 mg kg−1 was observed in the soil. A substantial correlation between DTPA and organic carbon was also identified. They noted that Fe fluctuated between 0.1 and 2.8 mg kg-1, 0.4 and 4.8 mg kg-1, and 4.5 mg kg-1 and above, respectively. Overall, the concentrations of DTPA-Zn, -Cu, and -Fe diminished with increasing soil depth. The report by Satyavathi and Reddy (2004) indicated that Cu and Mn levels were sufficient in the soils of ten pedons in the Telangana region of Andhra Pradesh. The study indicated an absence of a clear trend in the distribution of DTPA-extractable micronutrients with respect to depth. Minakshi *et al*. (2005) noted a 4 percent deficiency of manganese and a 5 percent deficiency of iron in the soil of Patiala district, Punjab. Sharma *et al*. (2003) also noted a positive correlation between organic carbon and available micronutrients in the soils. Sharma *et al*. (2006) examined the soils of various blocks in Leh district to evaluate the availability of major micronutrients and found a positive correlation between the available micronutrients Fe, Mn, and Cu (0.072, 0.029, and 0.069 mg kg−1, respectively) and organic carbon content.

**Correlation between micronutrients (Fe, Zn, Cu, and Mn) physical and chemical properties of soils**

**Iron (Fe):** Sahu *et al*. (1990) conducted a study on the distribution of clay content, finding a significant and positive correlation between clay content and Fe. However, the relationship between pH and DTPA-extractable micronutrients was found to be negative. Bhogal *et al*. (1993) indicated that the levels of available Fe, Zn, Cu, Mn, and B exhibited significant negative correlations with pH, while showing positive correlations with organic carbon. Vijay Kumar *et al*. (1996) demonstrated a significant negative correlation between available Fe, Zn, Cu, and Mn with soil pH. Sarkar *et al*. (2000) concluded from their investigation that the availability of Zn and Fe exhibited a significant negative correlation with pH.

**Zinc (Zn):** Sharma *et al*. (1996) examined the positive correlation of all elements with silt and clay contents, alongside a negative correlation with sand content. Silt-sized feldspar exhibited a positive correlation with Cu, Zn, and Mg, whereas other sizes demonstrated a negative association with Zn, Fe, Mg, and Mn. Gupta *et al*. (2003) confirmed that DTPA-extractable micronutrient cations (Zn, Cu, Fe, and Mn) exhibited a positive correlation with organic carbon, while demonstrating an inverse relationship with soil pH and CaCO3 content. Venkatesh *et al*. (2003) reported a positive correlation between available Zn and Cu and organic carbon. Vijayakumar *et al*. (2011) investigated iron (Fe) and discovered a positive correlation with organic carbon (OC), while observing a negative correlation with pH. Zn exhibited a positive correlation with EC and pH, while demonstrating a negative correlation with OC.

**Copper (Cu):** Meena *et al*. (2006) conducted a study on the soils of the Tonk district in Rajasthan, reporting a significant negative correlation between soil pH and available copper (Cu). Available Cu exhibited a positive correlation with organic carbon and clay content. Vijayakumar *et al*. (2011) investigated the tsunami-affected regions of Sirkali Taluk in Tamil Nadu, finding that copper exhibited a positive correlation with organic carbon, while showing negative correlations with pH, electrical conductivity, and zinc.

**Manganese (Mn):** Datta and Ram (1993) indicated that the availability of manganese exhibited an inverse correlation with clay content in both upland and lowland soils of Tripura. Kher *et al*. (2004) investigated organic carbon and discovered a significant positive correlation between organic carbon and all micronutrient cations. The report by Satyavathi and Reddy (2004) indicates that DTPA-extractable micronutrient content rises with an increase in organic carbon and diminishes with a rise in pH. Sharma *et al*. (2006) indicated a positive correlation between Cu and Mn with organic carbon in the soils of Leh district, Ladakh.

**Interaction of Micronutrients in Plant Growth**

Micronutrients do not function independently; they interact with each other and with macronutrients in complex ways. These interactions can significantly influence nutrient availability, absorption efficiency, and overall plant health (Wawrzyńska and Sirkon, 2014). Understanding these interactions is crucial for maintaining a balanced nutrient profile in the soil and ensuring optimal plant growth.

**Micronutrient Uptake and Soil Influence**

The availability of micronutrients is influenced by several soil properties, including pH, organic matter content, moisture levels, and microbial activity. Understanding these factors is crucial in developing strategies to optimize micronutrient availability for sustainable crop production.

* **Soil pH:** Soil pH significantly affects the solubility and availability of micronutrients. Iron, manganese, and zinc are more soluble in acidic soils, while molybdenum is more available in alkaline conditions. In calcareous or high-pH soils, iron and zinc deficiencies are common due to their reduced solubility (Marschner, 2012).
* **Organic Matter:** Organic matter plays a vital role in micronutrient retention and mobility. Decomposing organic material releases chelating agents, such as humic and fulvic acids, which form complexes with micronutrients, preventing their precipitation and enhancing bioavailability to plants (Lehmann and Kleber, 2015).
* **Moisture Levels:** Soil moisture influences micronutrient diffusion and uptake by plant roots. In waterlogged conditions, iron and manganese become more soluble due to anaerobic conditions, while excessive dryness can lead to their reduced availability. Proper irrigation management is critical to maintaining an optimal micronutrient balance (Fageria, 2014).
* **Microbial Influence:** Soil microorganisms play a key role in the cycling and solubilization of micronutrients. Mycorrhizal fungi enhance root surface area and facilitate phosphorus and zinc uptake, while rhizobacteria contribute to iron solubilization through siderophore production. Enhancing microbial diversity in soils can improve micronutrient bioavailability (Kumar *et al*., 2016).
* **Clay Content and Cation Exchange Capacity (CEC):** Soils with higher clay content and CEC have a greater capacity to retain micronutrients, preventing leaching losses. However, excessive fixation can also reduce their availability, making proper soil management crucial in balancing nutrient retention and accessibility (Ćirić *et al*., 2023).
* **Chelation and Root Exudates:** Plants release organic acids and root exudates that help solubilize and mobilize micronutrients from soil particles. Crops with efficient root exudate production can improve their ability to acquire micronutrients under nutrient-limited conditions (Dakora and Phillips, 2002).

**Micronutrient Deficiency and Its Impact on Plant Health**

Deficiencies in micronutrients can have severe consequences for plant growth, yield, and quality. The symptoms of micronutrient deficiencies vary depending on the specific nutrient, but all can lead to decreased crop productivity and economic losses for farmers. The impact of micronutrient deficiency extends beyond visual symptoms and can affect the biochemical and physiological functions within the plant.

**Iron deficiency:** Leads to chlorosis, reduced photosynthesis, and lower energy production. Young leaves show yellowing between veins, a condition known as interveinal chlorosis. Severe deficiencies can result in stunted growth and weakened plants that are more prone to disease and environmental stress (Marschner, 2012; Briat *et al*., 2015, Fig 2)

**Zinc deficiency:** Causes stunted growth, distorted leaves, and decreased seed viability. Plants exhibit shortened internodes and smaller leaves, resulting in overall reduced biomass. Zinc-deficient plants are more susceptible to environmental stress and have impaired protein synthesis (Cakmak, 2000; Alloway, 2008, Fig 2).

**Copper deficiency:** Results in weak stems, poor flowering, and increased disease susceptibility. Leaves may show curling, tip dieback, and chlorosis. A lack of copper disrupts lignin formation, making stems weak and increasing the likelihood of lodging in cereals (Marschner, 2012; Broadley *et al*., 2012, Fig 2).

**Manganese deficiency:** Leads to interveinal chlorosis and poor nitrogen metabolism. Symptoms may include brown spots on leaves and slow growth. Manganese is essential for photosynthesis, and its deficiency reduces plant efficiency in utilizing sunlight for energy (Millaleo *et al*., 2010; Marschner, 2012, Fig 2).

**Boron deficiency:** Causes fruit malformation, poor root growth, and reproductive failure. It particularly affects flowering and fruit set, leading to decreased yields in crops like tomatoes, apples, and soybeans. Additionally, boron deficiency weakens cell walls, making plants more prone to damage and disease (Shorrocks, 1997; Dell & Huang, 1997, Fig 2).

**Molybdenum deficiency:** Leads to nitrogen accumulation in leaves and stunted growth. Plants may exhibit yellowing leaves, slow growth, and reduced enzyme activity. Since molybdenum is vital for nitrogen metabolism, its deficiency can result in nitrogen deficiencies even in nitrogen-rich soils (Gupta, 1997; Marschner, 2012, Fig 2).

**Chlorine deficiency:** Causes leaf mottling, reduced drought tolerance, and lower disease resistance. Although rare, chlorine deficiency weakens osmotic regulation, leading to wilting and overall poor water balance in plants (White & Broadley, 2001; Marschner, 2012, Fig 2).



**Figure 2. Symptoms of micronutrient deficiencies in plants (**Prusty *et al*., 2022)

**Deficiencies and toxicities**

Micronutrient deficiencies and toxicities are prevalent and have been recorded in diverse soils across the globe. The lack of essential micronutrients causes abnormal pigmentation, size, and shape of plant tissues, decreases leaf photosynthetic rates, and results in various harmful conditions (Masoni *et al*., 1996). Deficiency symptoms manifest across all parts of the plant, with leaf discoloration being the most frequently noted observation. Symptoms of deficiency and toxicity can often be mistaken for those caused by drought, disease, insect infestations, and other forms of damage, making accurate diagnosis challenging without sufficient experience (Masoni *et al*., 1996). A description of deficiency and toxicity symptoms related to various crop plants is included in Table 2.

**Table 2. General description of mineral toxicity symptoms on plants**

|  |  |
| --- | --- |
| Iron (Fe) | Excess Fe is a common problem for plants grown in flooded acidic soil. May induce P, K and Zn deficiencies. Bronze or blackish straw-colored leaves extending from margins to midrib. Roots may be dark red and slimy. |
| Zinc (Zn) | Excess Zn may enhance Fe deficiency. Leaves become light colored with uniform necrotic lesions in interveinal tissue, sometimes damping off near tips. Roots may be dense or compact and may resemble barbed wire. |
| Copper (Cu) | High Cu may induce Fe deficiency (chlorosis). Light colored leaves with red streaks along margins. Plants become stunted with reduced branching and roots are often short or barbed (like wire). Laterals may be dense and compact. |
| Manganese (Mn) | Excess Mn may cause leaves to be dark green with extensive reddish-purple specks before turning bronze yellow, especially interveinal tissue. Uneven distribution of chlorophyll. Margins and leaf tips turn brown and die. Sometimes Fe deficiency appears, and main roots become stunted with increased number and density of laterals. |
| Boron (B) | High B may induce some interveinal necrosis, and severe cases turn leaf margins straw color (dead) with distinct boundaries between dead and green tissue. Roots appear relatively normal. |
| Molybdenum (Mo) | Excess Mo induces symptoms similar to P deficiency (red bands along leaf margins), and roots often have no abnormal symptoms. |
| **Chlorine (Cl)** | High Cl results in burning leaf tips or margins, reduced lead size, sometimes yellowing, resembles K deficiency, and root tips die |

(Source: Clark and Baligar, 2000)

**Consequences of Micronutrient Deficiencies in Sustainable Agriculture**

Micronutrient deficiencies in agricultural systems have far-reaching impacts that extend beyond plant health, affecting the overall sustainability of agriculture. These consequences include:

**Reduced Crop Yields:** Deficiencies in essential micronutrients, such as zinc, iron, and manganese, can lead to reduced crop productivity. This not only results in direct economic losses for farmers but also contributes to food insecurity. Reduced yields increase dependence on imported food, placing additional pressure on local economies and undermining agricultural sustainability (White & Broadley, 2009; Mertz *et al*., 2007).

**Lower Nutritional Quality:** Crops grown in micronutrient-deficient soils often have lower mineral content, which negatively impacts both human and animal nutrition. This leads to malnutrition and associated health issues, particularly in regions where agriculture is the primary source of food. Micronutrient malnutrition, or "hidden hunger," is a significant concern globally, especially in low-income areas (Haug *et al*., 2012).

**Increased Susceptibility to Pests and Diseases:** Micronutrient deficiencies weaken plant defense mechanisms, making crops more vulnerable to pests and diseases. This results in the increased need for chemical pesticides, which not only raises production costs but also contributes to environmental pollution and health risks (Rengel, 2002).

**Soil Degradation:** Prolonged micronutrient deficiencies deplete soil fertility, decreasing its capacity to support sustainable farming. Deficient soils experience a reduction in organic matter content and microbial activity, which are essential for maintaining soil health and nutrient cycling. Over time, this degradation leads to a vicious cycle of declining soil fertility (Marschner, 2012).

**Environmental Impact:** The overuse of synthetic fertilizers to compensate for micronutrient deficiencies can lead to various environmental issues. Excess fertilizers often leach into water sources, causing eutrophication, which leads to algal blooms and harm to aquatic ecosystems. Furthermore, the overapplication of fertilizers can lead to soil acidification and a loss of biodiversity in agricultural landscapes (Vitousek *et al*., 2009).

**Economic Burden on Farmers:** Farmers dealing with micronutrient deficiencies are forced to invest in additional corrective measures, such as purchasing fertilizers or soil amendments. These extra costs can be financially burdensome, particularly for small-scale farmers in developing countries who already face limited resources (Bouis, 2008).

**Reduced Climate Resilience:** Plants suffering from micronutrient deficiencies are less equipped to cope with environmental stressors like drought, heat, and extreme weather events. This diminished resilience makes agricultural systems more vulnerable to the impacts of climate change, further increasing the likelihood of crop failures (Bohnert *et al*., 2012).

Addressing micronutrient deficiencies is essential for ensuring sustainable crop production and maintaining soil health. Strategies such as proper soil management, biofortification techniques, and the use of organic amendments can help restore micronutrient balance, improve plant health, and enhance agricultural sustainability.

**Sustainable Management of Micronutrients**

To maintain sustainable agriculture, it is essential to adopt strategies that ensure optimal micronutrient availability while minimizing environmental impact. Key approaches include:

1. **Soil Testing and Monitoring:** Regular soil analysis helps identify nutrient deficiencies and enables precise fertilization strategies, reducing overuse of fertilizers (Murthy *et al*., 2024).
2. **Integrated Nutrient Management (INM):** Combining organic and inorganic fertilizers optimizes nutrient availability and soil health while reducing dependency on synthetic inputs (Samanta and Sengupta, 2024)
3. **Crop Rotation and Diversification:** Crop rotation, a long-standing technique ingrained in agricultural customs across the globe, entails growing various crops in succession on the same plot of land over the course of several seasons or years.
By altering nutrient demands, strengthening soil structure, and increasing soil microbial diversity, this technique not only breaks the cycles of pests and diseases but also improves soil health. Farmers can reduce soil nutrient depletion, inhibit weed growth, and increase overall soil fertility by rotating crops with varying rooting depths, nutritional needs, and allelopathic qualities (Mamatha *et al*., 2024).
4. **Use of Biofertilizers:** Biofertilizers, comprising microbial inoculants such as nitrogen-fixing bacteria (e.g., *Rhizobium, Azospirillum*) and mycorrhizal fungi, play a pivotal role in sustainable agriculture by enhancing nutrient uptake and reducing reliance on chemical fertilizers. These beneficial microorganisms improve soil fertility through mechanisms like nitrogen fixation, phosphate solubilization, and the production of growth-promoting substances. Their application has been shown to increase crop yields and improve soil health, offering an eco-friendly alternative to conventional fertilizers (Shahwar *et al*., 2023).
5. **Cover Cropping**: A fundamental aspect of traditional soil management is cover cropping, which involves cultivating non-commercial crops to shield and safeguard the soil during fallow periods or between cash crops. Cover crops contribute significantly to soil health by acting as living mulches that inhibit weed growth, mitigate erosion, and enhance soil structure. Cover crops improve soil aggregation, elevate soil organic matter content, and promote microbial diversity through their extensive root systems. Additionally, specific cover crops, particularly legumes, possess the capacity to fix atmospheric nitrogen, which enhances soil nutrient content and diminishes reliance on synthetic fertilizers (Mamatha *et al*., 2024).
6. **Foliar Application of Micronutrients:** Foliar application of micronutrients involves spraying nutrients directly onto plant leaves, facilitating rapid absorption and immediate correction of deficiencies. This method is particularly effective in addressing nutrient shortages during critical growth stages, leading to enhanced plant health and increased productivity. A study by Aziz *et al*. (2019) demonstrated that foliar application of micronutrients significantly improved crop stand, yield, and biofortification in various wheat cultivars, underscoring its efficacy in modern agricultural practices. Incorporating foliar micronutrient sprays can be a strategic approach to optimize nutrient management, especially when soil conditions limit nutrient availability.
7. **Organic Matter Addition:** Incorporating organic amendments such as compost, manure, and cover crops into agricultural soils enhances soil structure, water retention, and microbial activity, thereby facilitating nutrient cycling. These practices contribute to improved soil fertility and overall plant health (Ayeni and Olagoke-Komolafe, 2024).
8. **Precision Agriculture Technologies:** Advanced tools like remote sensing and GPS-based fertilization ensure precise nutrient application, minimizing waste and environmental impact (Indira *et al*., 2023).
9. **Breeding and Genetic Approaches:** Developing crop varieties with enhanced micronutrient efficiency is a pivotal strategy in addressing nutrient deficiencies and improving the nutritional quality of food. Through conventional breeding and modern genomic techniques, researchers have successfully increased the concentrations of essential micronutrients such as iron (Fe), zinc (Zn), and provitamin A in staple crops like rice, wheat, and maize without compromising yield. These biofortified crops not only contribute to better human nutrition but also exhibit improved resilience to nutrient-deficient soils, thereby supporting sustainable agricultural practices (Bouis, and Welch, 2010).
10. **Water Management:** Effective irrigation practices are crucial for maintaining soil nutrient balance and promoting optimal plant growth. Proper irrigation prevents nutrient leaching—a process where excess water washes away essential nutrients beyond the root zone—thereby enhancing nutrient uptake by plants. A recent study highlights that optimizing irrigation regimes significantly reduces nutrient leaching and improves nutrient absorption in crops like maize. The research emphasizes the importance of aligning water application with crop needs to enhance nutrient use efficiency and minimize environmental impacts (Amare *et al*., 2024).
11. **Legislative and Policy Support:** Legislative and policy support plays a crucial role in promoting sustainable nutrient management, which is essential for maintaining long-term soil health and ensuring food security. Government policies that incentivize farmers to adopt sustainable practices, such as integrated nutrient management (INM) and precision agriculture, contribute to enhancing soil fertility and minimizing environmental degradation. These policies not only support the efficient use of fertilizers but also promote the adoption of eco-friendly techniques, which help mitigate nutrient runoff and greenhouse gas emissions (Singh *et al*., 2020; Kumar *et al*., 2021). Furthermore, financial incentives, such as subsidies or payments for ecosystem services, can encourage farmers to shift towards sustainable practices that benefit both the environment and food production systems (Smith *et al*., 2019).
12. **Enhancing Nutritional Quality of Produce through Micronutrient Management**

Achieving high nutritional quality in sustainably grown produce is crucial for human health. Micronutrient-rich crops can help combat malnutrition and micronutrient deficiencies in populations, particularly in developing countries. Efforts to biofortify crops with essential micronutrients have been successful in many regions, leading to improved health outcomes.

**Biofortification**

“Biofortification, a new approach that relies on conventional plant breeding and modern biotechnology to increase the micronutrient density of staple crops, and holds great promise for improving the nutritional status and health of poor populations in both rural and urban areas of the developing world” (Graham and Welch, 1996). “Biofortification provides a sustainable solution to Fe and Zn deficiencies in food around the world as it is the process of enriching the nutrient contents of staple crops. Biofortification of staple food crops with micronutrients by either breeding for higher uptake efficiency or fertilization can be an effective strategy to address widespread dietary deficiency in human populations” (Bouis *et al*., 1999). “The lack of micronutrients such as Fe and Zn is a widespread nutrition and health problem in developing countries. Reports have highlighted the current strategies for the biofortification of crops, including mineral fertilization, conventional breeding, and transgenic approaches. Any approach which could increase root growth and result in a high transfer of Fe and Zn from the soil to the plant is crucial for biofortification” (Graham, 1984).

**Case Studies in Micronutrient Biofortification**

**1.** **Zinc Biofortification in Wheat**: Biofortification strategies involving the application of zinc fertilizers (agronomic biofortification) and the development of wheat varieties genetically enhanced for higher zinc accumulation have demonstrated effectiveness in improving both grain yield and nutritional quality. These approaches are particularly relevant in zinc-deficient regions, contributing to better human health outcomes and agricultural sustainability (Cakmak, 2008; Zou *et al*., 2012).

2. **Iron Enrichment in Beans**: The development and dissemination of iron-rich common bean (*Phaseolus vulgaris*) varieties through conventional breeding have shown significant potential in addressing iron deficiency, especially in populations that rely heavily on beans as a staple food. These iron-biofortified beans not only help improve dietary iron intake but also maintain agronomic performance under challenging growing conditions (Blair *et al*., 2010; Petry *et al*., 2015).

**Policy and Economic Implications**

The importance of micronutrients in sustainable agriculture extends beyond agronomic practices, encompassing significant policy and economic dimensions at both national and international levels. Effectively addressing micronutrient deficiencies within food systems necessitates coordinated efforts among governments, agricultural research institutions, and farming communities. Policymaking that integrates micronutrient management into national agricultural strategies can help ensure food and nutrition security. Furthermore, providing economic incentives—such as subsidies for micronutrient fertilizers, support for biofortification programs, and capacity-building initiatives—can encourage farmers to adopt nutrient-enriching practices, thereby enhancing the scalability and sustainability of these interventions (Bouis and Saltzman, 2017; Fanzo *et al*., 2020). Policies promoting research and development in biofortification and sustainable fertilization also play a critical role in improving the nutrient density of food crops and in combating hidden hunger (Saltzman *et al*., 2013).

**Conclusion and Future Perspectives**

Sustainable management of micronutrients is fundamental to achieving long-term agricultural productivity and food security. Ensuring balanced micronutrient availability can improve plant resilience, soil fertility, and human nutrition while reducing environmental impacts. Future research should focus on advanced soil health monitoring, development of biofortified crops, and innovative fertilization techniques to enhance nutrient efficiency. Policies that support sustainable nutrient management and farmer education will be a key in promoting long-term sustainability in global agriculture.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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