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Micronutrient deficiency in Indian soil and human nutrition Interface

Anjali ✉,[1], Suvidha

Department of Food and Nutrition, Banasthali Vidyapith, Rajasthan, India,

Department of Human Development and Family Studies Institute, Banasthali Vidyapith, Rajasthan, India,

✉ anjali.parmar23sa@gmail.com, suvidha@banasthali.in

Healthy soils are the basis for healthy food production

-Food and Agriculture Organization

Abstract

The insufficiency of nutrient elements and ineffective nutrient management practices in the agricultural soils across the globe is a significant cause of low crop productivity, decreased nutritional quality of agricultural produce, and causes malnutrition in humans and animals. Trace minerals in the soil are essential for crop productivity and the mineral concentration in crops, which can impact the nutritional status of human populations that depend on these crops. Soil fertility and plant nutrition are determined by essentiality criteria; there were 16 essential elements previously, and this has now been updated to 17. Researchers, policymakers, and farmers primarily engage with the main nutrients, namely NPK, to manage crops effectively. However, this focus leads to an aggravation of micronutrient deficiencies, which is now a significant concern as it adversely affects human and animal nutrition, in addition to plant health. Micronutrients are essential not only for plant growth but also for enhancing disease resistance in cultivated crop species. In India, this issue has become increasingly alarming due to the widespread micronutrient imbalance across the country. This deficiency impacts not only plant nutrition but also has extensive implications for nutritional insecurity among livestock and marginalized populations. Therefore, it is crucial to study the significance of micronutrients to address these challenges and manage them in crop production. This study investigates the relationship between deficiencies of single and multiple micronutrients, including sulphur (S), zinc (Zn), boron (B), iron (Fe), copper (Cu), and manganese (Mn), in agricultural soils of India and their impact on the nutritional value of plants and human nutrition. This chapter advances our knowledge of soil nutrition in relation to our food.

Keywords: Human nutrition, Indian soil, Micronutrients deficiency, Plant nutrition, soil fertility

Introduction

Agriculture is recognized as one of the most ancient human endeavours. It has facilitated the transition from nomadic living to settled communities. The planting of wheat and barley initiated in 7500 BC, succeeded by maize and rice cultivation in 4400 BC and 2000 BC, respectively [1]. Justus Von Liebig is seen as the originator of modern agricultural practices, having developed the theory of mineral nutrition and articulated the law of minimum [2]. As stated by Stout (1962), "When viewing plants as biological machines, their structures are made up of macro-elements, their functional components are proteins and enzymes cantered around nitrogen atoms, while the 'MICRONUTRIENTS' serve as the necessary lubricants for various energy transfer processes within the plants." This assertion from a scientist who played a key role in recognizing molybdenum as a vital micronutrient effectively highlights the significance of micronutrients in plant metabolism [3]. During the 20th Century, the increase in crop yields was revolutionized by the discovery of micronutrients, beginning with iron (Fe) in 1868 and concluding with molybdenum (Mo) in 1938.

Micronutrients play a crucial role as essential elements that plants require in small quantities for their growth, development, and metabolic activities. However, their significance should not be underestimated. In contrast, macronutrients are needed in amounts of 1000 $\mu g\ g^{-1}$ of dry matter and above, whereas micronutrients are required in tissue concentrations of 100 $\mu g\ g^{-1}$of dry matter or lower [4]. Micronutrients are vital components that plants need in minimal amounts for their growth, development, and metabolic processes. Despite their low requirements, these micronutrients are crucial for various physiological processes, including photosynthesis, enzyme activation, and nutrient uptake. However, the issue of micronutrient deficiencies in soil has become a significant global concern, especially in agricultural areas where intensive farming and imbalanced fertilizer use have led to nutrient depletion and soil degradation. In countries like India, where agriculture is the backbone of the economy and supports the livelihoods of millions, these deficiencies pose serious challenges to agricultural sustainability and food security. With a population of over 1.3 billion and a rapidly increasing demand for food, it is essential to address these deficiencies to ensure adequate food production, nutritional security, and sustainable agricultural development. The causes of micronutrient deficiencies in Indian soil are complex and often interconnected. Soil characteristics such as texture, pH, and organic matter content affect the availability and uptake of micronutrients by plants. For example, alkaline soils common in regions like Punjab and Haryana are prone to deficiencies in iron and zinc due to the reduced solubility of these micronutrients at higher pH levels [5].

Soil has long been regarded as the main source of nutrients. With the rising demand for food, the use of chemical fertilizers to boost production has also escalated, marking the green revolution as a pivotal moment for fertilizer application in Indian agriculture. According to FAO reports (2005), the rise in the use of chemical fertilizers (NPK) since 1960 has led to an increase in crop productivity. However, this has resulted in the depletion of soil nutrient reserves, prompting crops to respond positively to micronutrient applications [(6)]. The green revolution brought about the introduction of high-yielding varieties and a greater reliance on nitrogen (N), phosphorus (P), and potassium (K), which resulted in a remarkable increase in crop production. However, this advancement has also led to a deficiency of micronutrients in many Indian soils. [(7, 8)]. Micronutrient conditions in India It is estimated that 40-55% of Indian soils are moderately deficient in zinc, while 25-30% are lacking in boron. Deficiencies of other micronutrients are found in under 15% of soils [(9)]. Most micronutrient deficiencies or toxicities in India are categorized as mild to moderate. With 80-90% of Indian soils deficient in nitrogen and phosphorus, these deficiencies are evident in leaf colour, size, growth habit, flowering, and yield. Thus, rectifying these issues is more visibly compelling. Conversely, 70-80% of micronutrient disorders in horticultural crops manifest as hidden hunger. Leaf and soil analysis is essential for detecting these issues at the right time.

Soil plays a crucial role in agricultural productivity. Ensuring the health of soil is vital for enhancing productivity. Over time, food production levels have risen, resulting in the extraction of more nutrients from the soil. This has caused a nutrient imbalance, leading to a decline in soil health. Additionally, improper use of fertilizers can lead to a loss of soil fertility. Apart from water, agricultural sustainability primarily depends on

17 essential nutrient elements required for plant growth. These nutrients are critical for the development and maintenance of crop plants. Carbon, hydrogen, and oxygen are sourced from air and water. The remaining nutrients are divided into primary (N, P, K), secondary (Ca, Mg, S), and micronutrients (Zn, Cu, Fe, Mn, Ni, B, Mo, and Cl). These nutrients are further categorized into macronutrients (which encompass primary and secondary nutrients) and micronutrients. Each micronutrient serves a distinct function within the plant, making it essential. For a plant to successfully complete its life cycle, which culminates in maturity and the harvesting of produce, these nutrients must be present in optimal concentrations. No single essential nutrient can substitute for another; thus, the deficiency of one micronutrient can only be remedied by applying a fertilizer that contains that specific nutrient or by implementing measures that enhance its availability to the crop. When a nutrient is lacking, all vital plant processes reliant on that micronutrient are either slowed or disrupted. For instance, boron (B) is crucial for cell division and organ formation (differentiation) occurring at the growing tips, and a deficiency in B can harm these tips. Likewise, plants exhibit subtle deficiency signs when they lack a specific micronutrient in sufficient quantities. In cases of marginal deficiency, visible signs may not appear, making detection challenging. This phenomenon is referred to as hidden hunger, which results in lower-than-expected yields. By having plants analyzed in a reputable laboratory and adhering to the provided recommendations, hidden hunger can be mitigated. It is also noteworthy that not all crops exhibit the same sensitivity to nutrient deficiencies, even under comparable growing conditions. The observation that some crops are more susceptible to micronutrient deficiencies indicates that the critical concentration of a nutrient varies among crops. Additionally, this concentration differs based on soil and climatic

conditions. The nutritional status of soil directly impacts human health. Numerous countries, particularly developing ones, have reported epidemics of vitamin and mineral deficiencies.

Globally, over two billion people are affected by micronutrient deficiencies, a form of malnutrition stemming from inadequate intake of these essential nutrients. Research indicates that such deficiencies can influence learning, IQ, motor skills, and the functioning of the immune system. For children who are deficient in micronutrients, the effects can endure into their adult years (10,11). In particular, zinc deficiency was estimated to have led to 116,000 deaths in children under five years old worldwide in 2011(12.). Moreover, it is anticipated that by 2050, an additional 175 million individuals may become zinc deficient as global levels continue to rise (13).

It is estimated that more than 35% of soils in India are deficient in zinc, while around 11% are estimated to be deficient in iron (14). which can lead child malnutrition as child stunting in India is roughly 35% (15), and malnutrition was the foremost risk factor for the loss of Disability-Adjusted Life-Years in 2016, accounting for an estimated 0.5% of all deaths in India (16). Moreover, almost 138 million individuals in India—10% of the country's population—are rural residents living below the poverty line (17,18). A significant number of these individuals are farmers who own small parcels of land and rely on their own production for food, especially staple cereals (19,20).

Micronutrients Deficiency in Indian Soil

Basic rocks, which are intermediate between ultrabasic and acidic rocks, have a higher concentration of Mn, Co, Ni, Cu, and Zn, while sedimentary rocks are rich in Molybdenum and Boron. The abundance of these minerals is determined by their chemical affinity [21]. The pH level of the soil is a key factor in the availability of micronutrients, with lower pH generally favouring their availability. There are exceptions, such as Molybdenum, which is available at alkaline pH, and Boron, which is available at neutral pH. Soils in areas with high rainfall are often leached, leading to deficiencies in micronutrients. Additionally, the cultivation of nutrient-exhaustive crops combined with limited application of only N, P, and K fertilizers has exacerbated the deficiency of micronutrients. Between 2011 and 2017, ICAR-IISS in Bhopal analysed more than 200,000 samples from 508 districts across the country, reporting that, on average, 36.5%, 12.8%, 7.1%, 4.2%, and 23.2% of soils are deficient in Zn, Fe, Mn, Cu, and B, respectively [22].

The most deficient nutrient in Indian soils is Zinc, followed by Boron. Major areas affected by Zinc deficiency in India include the calcareous and ancient alluvial soils of Bihar, the acidic and highly leached soils of West Bengal and Odisha, and the red lateritic soils of Karnataka [21]. Initially, the occurrence of Zinc deficiency was more prevalent in cereals, especially in the rice and wheat belts of the country; however, as time has progressed, the distribution of Zinc deficiency has extended throughout the entire country across various crops [23].

In Indian soils, boron deficiency has escalated from 2 percent in 1980 to 52 percent currently. This issue is especially significant in the sandy soils of Haryana and Rajasthan, the red and lateritic soils found in South India, the sub-mountainous soils of the Northern Himalayas and northeastern hill states, along with the calcareous soils of Bihar, Eastern Uttar Pradesh, Saurashtra, and Tamil Nadu [24].

Iron deficiency is often found in upland crops, especially those that grow on calcareous alkaline soils in arid regions, soils with high levels of calcium carbonate, highly permeable coarse-textured soils, and soils low in organic carbon. Despite Indian soils being relatively rich in available iron, its availability in certain states such as Gujarat, Haryana, Maharashtra, Telangana, and Andhra Pradesh is threatening crop yields [25].

Manganese deficiency in Indian soils is not a significant problem, except in certain regions with coarse textured alluvial, leached, and deep black clayey soils. Manganese deficiency has been documented after rice has replaced kharif season crops in the maize-wheat and groundnut-wheat cropping systems of coarse textured soils [21]. The leaching of manganese occurs during the rainy season while rice is grown, leading to acute manganese deficiency in the subsequent wheat crop. In India, copper deficiency is not a major issue, affecting only 4.2% of soils [26]. Copper deficiency is typically found in soils with high organic matter (Histosols), lateritic, highly weathered soils (Ultisols), sandy textured soils, and calcareous soils. This deficiency is more common in the peaty soils of Kerala [21].

Molybdenum is recognized as the least commonly found micronutrient in the lithosphere [27]. Its deficiency is prevalent in acidic, sandy, and leached soils. Mo deficiency is particularly localized in certain regions of Madhya Pradesh, Maharashtra, and the acidic soils of Odisha and West Bengal, especially in areas where pulse crops are cultivated [25]. There have been no reports of chlorine and nickel deficiencies in Indian soils to this point.

Table 1: Functions of Micronutrients

Micronutrients are vital substances for plants, though they are needed in minimal amounts. The eight elements recognized as micronutrients include iron, zinc, manganese, copper, nickel, boron, molybdenum, and chlorine. These elements are crucial for the growth of plants.

Micronutrients	Functions	References
Zinc	Zinc is essential for the reproductive growth of plants, low supply of Zn results in reduced size of anther, poor pollen producing capacity, reduced pollen size and its viability. Zinc regulates metabolic reactions in plants and helps in utilisation of N and P in plants.	(28)
Iron	Iron plays an important role in the electron transport chain of respiration and photosynthesis; however, it becomes toxic when accumulated to higher level in plants.	(29)
Manganese	Mn-deficient in plants, especially in the roots is associated with increased pathogenic attack, particularly soil-born fungi, since lignin serves as a barrier against pathogenic infection. It Activates and regulates enzymes also responsible for nitrogen metabolism and chlorophyll synthesis.	(30)
Boron	Essential for proper pollination, fruit set, fruit yield and quality of temperate fruits. Maximum grain yield in rice has been reported with soil application of boron at flowering stage. Is an enabler for mobility of energy in the plants and helps in calcium and protein synthesis.	(31,32)
Copper	Copper as an essential micronutrient for normal growth and metabolism of plants. It helps in formation of vitamin A in plants. It Enables formation of ethylene in ripening fruit which aids in carbohydrate and nitrogen metabolism.	(33)
Molybdenum	Molybdenum promotes fixation of nitrogen and also improves the Phosphorus uptake by plants. Helps in nitrogen fixation in legumes. It involved in nitrogen metabolism of plants.	(34)
Nickel	Nickel is important for many bacterial enzymes, including key enzymes in the nitrogen-fixing symbiont, *Bradyrhizobium japonicum*, required by seeds to germinate and grow. It is responsible for absorption of iron.	(35)

Chlorine	Chlorine regulates the water balance in plants and imparts drought resistance in these. It Plays an important role in opening and closing of stomata (which is important for photosynthesis). It also Increases water-holding capacity of plant tissue.	(36)

Table 2: Major crops affected by micronutrient deficiencies

In India, crops grown in the majority of soils are affected by deficiencies of one or more micronutrients. The characteristics and degree of these deficiencies vary according to factors such as soil type and agro-ecological conditions. Micronutrient deficiencies are often seen in cereals, oilseeds, pulses, and vegetable crops that are grown intensively. Various crops demonstrate different levels of sensitivity to these deficiencies. The symptoms of micronutrient deficiencies can influence the quality of the produce, affecting more than just the yield (for example, a lack of boron can cause brown heart in turnips and corking in apples). Consequently, to ensure quality produce and enhanced yields, farmers cultivating fruits and vegetables tend to implement the use of micronutrients.

Micronutrients	**Crop impacted**
Zinc	Corn, onion, soyabean, paddy, grapes, peach
Iron	Tree crop, sorghum, blueberries, rose, grapes, nut trees
Manganese	Peas, oats, apple, sugar beet, beet root, citrus
Boron	Alfalfa, cauliflower, celery, grapes, apples, peanut, beet, rapeseed
Copper	Wheat, corn onion, citrus, carrot, lettuce
Molybdenum	Alfalfa, broccoli, cabbage, citrus, legumes
Nickel	Legumes (soyabean, cowpea pod)
Chlorine	Wheat, sorghum, corn

Causes of Micronutrient Deficiency in Indian Soil

Micronutrient deficiencies in Indian soil are affected by various factors, including soil properties and human activities. The characteristics of soil, such as pH, texture, and organic matter content, play a crucial role in determining the availability and absorption of micronutrients by plants. For example, alkaline soils found in areas like Punjab and Haryana are susceptible to deficiencies in zinc and iron due to the reduced solubility of these micronutrients at elevated pH levels [(37)]. Intensive agricultural practices, such as monoculture cropping, unbalanced fertilizer application, and poor soil management, worsen the issue of micronutrient deficiencies in Indian soils. Research has shown that the continuous cultivation of high-yielding crops, like rice and wheat, without adequate crop rotation or replenishment of micronutrients results in the depletion of vital nutrients, including zinc, iron, and manganese [(38)]. Additionally, the extensive use of phosphatic fertilizers without simultaneous application of micronutrients can lead to zinc deficiency in the soil by disrupting its uptake and availability to plants [(39)].

In addition, the extensive use of phosphatic fertilizers without the simultaneous application of micronutrients can lead to zinc deficiency in the soil by disrupting its uptake and availability to plants [(39)]. Soil erosion and leaching are other factors that contribute to the depletion of micronutrients in Indian soils. These processes result in the loss of topsoil layers, which are rich in organic matter and micronutrient reserves, thereby worsening deficiencies [(40)].Environmental factors, such as climate change, also influence the availability of micronutrients, with altered precipitation patterns and temperature regimes affecting soil nutrient dynamics [(41)].Moreover, human activities, including industrial pollution and mining, can introduce heavy metals into the soil,

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displacing crucial micronutrients and making the soil unfit for agricultural use. Heavy metal contamination poses significant risks to both soil health and human health, underscoring the importance of environmental regulations and remediation efforts [(40)]. In conclusion, micronutrient deficiencies in Indian soil are driven by a complex interaction of natural and human-induced factors. Addressing these deficiencies necessitates a holistic approach that combines soil management practices, agronomic interventions, and environmental stewardship.

To summarize, the lack of micronutrients in Indian soil is influenced by a complicated mix of natural and human-related factors. To effectively address these deficiencies, a well-rounded approach is essential, incorporating soil management strategies, agronomic measures, and environmental responsibility.

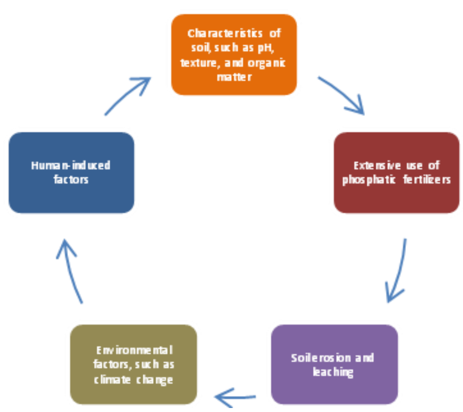

Figure 1. Factors impacting micronutrients availability

Consequences of Micronutrient Deficiency

Deficiencies in micronutrients within Indian soil have significant implications, influencing both agricultural productivity and human health. Among the most immediate effects are diminished crop yields and subpar crop quality. Studies have demonstrated that zinc deficiency can cause considerable yield losses, varying from 5% to 30% in crops such as rice, wheat, maize, and pulses (42). Similarly, iron deficiency in the soil negatively impacts the bioavailability of iron in crops, resulting in yield reductions and lower crop quality (43). Moreover, micronutrient deficiencies weaken the nutritional quality of crops, contributing to hidden hunger and malnutrition in vulnerable groups. Iron-deficiency anaemia, a widespread nutritional disorder in India, is directly related to insufficient dietary intake of bioavailable iron from crops (44). Likewise, zinc deficiency in soil produces crops with diminished zinc content, leading to zinc-deficient diets and associated health risks, including impaired growth and immune function (42).

Additionally, intensive agricultural practices, such as mono cropping and the excessive application of chemical fertilizers, aggravate nutrient imbalances and result in the depletion of micronutrients in the soil (45). Soil erosion, leaching, and environmental factors like climate change further complicate the issue by speeding up nutrient loss and soil degradation (40). The implications of micronutrient deficiencies reach beyond agricultural productivity, affecting human health and environmental sustainability. Imbalanced fertilization strategies aimed at correcting macronutrient deficiencies can inadvertently worsen micronutrient imbalances and soil degradation. For example, the overapplication of phosphatic fertilizers without the necessary micronutrient supplementation can lead to zinc deficiency in the soil and contribute to nutrient runoff and water pollution (39). Research has shown that zinc deficiency alone can lead to considerable yield losses in staple crops like rice, wheat, and maize, which are essential for food security in India (42). Moreover, deficiencies in micronutrients compromise the nutritional quality of crops, leading to hidden hunger and malnutrition among at-risk populations, particularly women and children [46]. Iron deficiency, for instance, is a leading cause of iron-deficiency anaemia, a widespread nutritional disorder that affects millions of individuals in India [44].

In addition, a lack of micronutrients in the soil has significant repercussions for ecosystem health and biodiversity. These essential micronutrients are crucial for enzymatic activities and biochemical pathways that support plant growth and development. Their absence can result in reduced crop yields, lower nutritional quality, environmental harm, and disruption of nutrient cycling processes, thereby affecting soil microbial communities and the overall health of ecosystems [47].

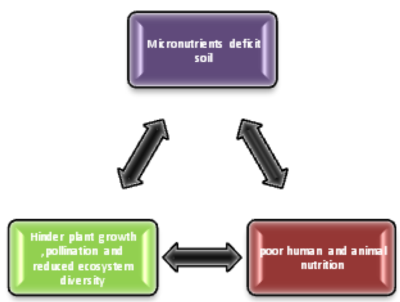

Figure 2: Micronutrients deficit soil causes poor plant, animal and human nutrition

Table 3: Micronutrients Deficiency Symptoms and requirement

It is important to prioritize the elevation of soil micronutrient levels to ensure the long-term sustainability of soil fertility and productivity. Different micronutrients are necessary in distinct quantities. Addressing these deficiencies is essential for realizing sustainable agricultural growth and improving health outcomes for individuals. The approximate concentrations of micronutrients requirement in soil and deficiency symptoms are detailed in below table.

Micronutrients	Deficiency Symptoms	Requirement in soil (mg/kg)
Zinc	The leaf is narrow and small	0.6
Iron	Leaf become bleached partially or completely	4.5
Manganese	Necrotic spots and stunted root development	2.0
Boron	Terminal leaves lose colour and deformed young leaves, fruits and stunted root growth	0.52
Copper	Its deficiency causes Interveinal chlorosis, rosetting and permanent wilting of leaves. The leaf detaches easily from the stem. Copper deficiency causes pollen sterility, yellowing and curling of leaves and lower density of ear production in cereals.	0.2
Molybdenum	Leaf become a light green. Dead necrotic spots appear over the leaf except on the veins. Molybdenum deficiency leads restricted flower formation and stunted plant growth.	0.1
Nickel	Nickel deficiency can cause accumulation of toxic urea in plant tissues. It results in poor germination, reduced growth, vigour and flowering, dwarfed internodes and poor kernel filling. Nickel deficiency is linked to dwarf foliage production and growth of reddish pigmentation in young leaves.	0.1
Chlorine	Chlorine deficiency showed chlorosis and burning of leaf tips, leading to bronzing and drying; over-wilting and leaf fall reduces the yield.	8.0

Source: Journal of the Indian Society of Remote Sensing, 2013

Management of Micronutrients Deficiency

There is distinct deficiency symptoms associated with each micronutrient; however, diagnosing based solely on these symptoms can be misleading, as each symptom may be linked to multiple causes. For instance, the deficiency of one nutrient can result from an excess of another, and damage from diseases and pests can be confused with nutrient deficiencies [48]. Micronutrients are required by plants in smaller quantities, and a slight increase can lead to toxicity. Diagnosing deficiencies in micronutrients is often difficult, which is why this issue is termed 'hidden hunger' [49]. Consequently, managing micronutrient deficiencies requires a localized and micro-level approach.

The absorption of micronutrients by plants plays a crucial role in their overall nutrition. The chemical makeup of the soil's parent material influences the levels of deficiency or toxicity of specific micronutrients. Therefore, conducting soil tests to assess the inherent micronutrient content is the initial step in management. Understanding the micronutrient levels in a given area is beneficial for both the industry and the government in formulating micronutrient fertilizers tailored to that region. A significant advancement in the estimation of micronutrients involves the use of chelating agents like EDTA and DTPA, which are effective for Zn, Cu, Fe, Mn, and Ni, while hot water and ammonium oxalate serve as extractants for determining molybdenum and boron respectively [50].

Although the soil may contain a high level of a specific micronutrient, it does not guarantee that it will be accessible to the crops. The availability is influenced by factors such as pH, texture, soil moisture conditions, and lime content. Consequently, assessing these characteristics is crucial for effective management of available micronutrients in the soil. The pH level significantly affects the availability of micronutrients. At lower pH levels, micronutrients are present in forms that are accessible but may also exhibit toxicity. Conversely, in soils with higher pH and calcareous conditions, the availability of micronutrients diminishes [52]. Therefore, it is recommended to maintain soil pH around 6.0 to ensure adequate availability for plants [21]. Elevated pH levels can result in deficiencies of nearly all micronutrients, with the exception of Molybdenum, while boron may be present in excess in sodic soils. Stabilizing pH can be achieved through the application of lime in acidic soils and gypsum along with other amendments in alkaline and sodic soils. Additionally, soil texture affects the availability of micronutrients. Clay soils tend to be richer in micronutrients compared to coarse-textured soils due to their superior water retention capacity. Likewise, acid-leached soils often lack micronutrients because of poor parent material, and leaching processes further deplete these nutrients (52).

The level of organic matter in soil is a key determinant of the status of available micronutrients. It acts as a store for micronutrients such as Fe, Mn, Zn, and Cu. Its solubilizing action enhances nutrient availability through chelate formation (53). found in a long-term fertilization study that the levels of Zinc, Boron, and Iron increased. Regularly incorporating organic matter into the soil decreases the likelihood of micronutrient deficiencies. The addition of green manure is particularly effective as it not only contributes organic matter but also helps recycle nutrients from deeper soil layers to the root zone of crops (54).

The type of cropping system adopted in a given area affects the micronutrient content of the soil. Intensive cropping practices, along with the excessive use of primary nutrients, make the soil prone to micronutrient shortages. In the Indo-Gangetic plains, the combination of intensive cultivation and insufficient agricultural practices has caused a deficiency in micronutrients, notably Zinc, Boron, and Manganese (55). The rice-wheat systems are particularly vulnerable to deficiencies in zinc, boron, manganese, iron, molybdenum, and copper. Enhancing crop diversity can lead to greater variability in the chemical nutrients found in the soil (56).

The enhancement of micronutrient availability can be achieved by developing cultivars that are effective in utilizing soil micronutrients [57]. It is essential to investigate nutrient interactions to effectively manage the availability of micronutrients in crops [58]. Excessive iron can negatively impact the absorption of zinc and manganese. Similarly, an overabundance of Sulphur and copper can cause molybdenum deficiency in crops [59]. Increasing phosphorus concentration can hinder the role of zinc at a specific site within the cell [60].

A primary objective of applying and managing micronutrients in soil is to achieve adequate concentrations in the final crop products, including seeds and grains, as this has a direct effect on human health and nutrition. At present, many agricultural systems in developing regions do not provide sufficient nutrients. Many are inadequate in supplying the necessary micronutrients (14 trace elements and 13 vitamins) to fulfil human needs, even though the production of energy and protein from cereal crops appears sufficient to nourish the world [25].The application of Zn, B, and Mo to the soil, along with foliar sprays, as well as foliar applications of Fe and Mn, has been suggested as the most effective approach to address these deficiencies in crops.

Micronutrients and Nutrition Interface

Micronutrients Fighting nutrition deficiencies

As reported by the World Health Organization, nearly two billion people - which is about one in four - are affected by 'Hidden Hunger' or deficiencies in vitamins and nutrients. This situation can lead to mental impairment, poor health, low productivity, and in the worst scenarios, even death. Children are particularly at risk for micronutrient deficiencies. A deficiency of zinc during childhood can lead to stunted growth, Vitamin A deficiency can result in night blindness and poor immunity, while iron deficiency is directly linked to inadequate mental and physical development. Adults also report micronutrient deficiencies. Deficiencies in both children and adults can often be traced back to soil deficiencies. Reports indicate that nearly 25% of the population in India suffers from zinc deficiency, and over 80% of pregnant women experience iron deficiency anaemia (IDA). Utilizing micronutrients in crops through fortification and other effective methods can help to restore the nutrient imbalance in both plants and humans

Micronutrients promote food security

Food security is often defined as the situation where all individuals, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for an active and healthy lifestyle. According to the FAO, it is estimated that by 2050, agricultural production will need to increase by nearly 50% to fulfil the requirements of the growing population. Furthermore, Sustainable Development Goal 2 is focused on eradicating hunger, achieving food security and improved nutrition, and promoting sustainable agricultural practices. It is well acknowledged that the availability of food is contingent upon soil health. Quality and nutritious crops can only be produced if the soil is healthy, which is a prerequisite for food security. Therefore, it is essential to implement a balanced use of fertilizers. Micronutrients are indispensable for the quantitative and qualitative enhancement of food productivity, making them a prerequisite for achieving food security.

Conclusion

Micronutrients are essential for plants, even though they are required in relatively small quantities (at 100 mg kg-1 dry weight). They play a vital role in numerous cellular and metabolic functions, such as gene regulation, hormone perception, energy metabolism, and signal transduction. Based on their specific needs in higher plants, essential micronutrients include boron (B), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). Each organism requires a sufficient supply of these microelements, which necessitates a complete metal homeostasis system that includes their uptake, accumulation in the plant, mobilization, storage, and intracellular transport (61). A lack of these elements or low Phyto availability can lead to decreased crop productivity on a global scale. Therefore, plants must have a steady and adequate supply of these micronutrients throughout their growth stages to ensure optimal productivity. Unfortunately, the expanding human population and the reckless exploitation of natural resources hinder plants from securing their necessary supply for the future, creating a pressing challenge for scientific expertise. Recent findings indicate that about two-thirds of the world's population is at risk of nutrient deficiency (62).

By the year 2050, the global population is expected to reach 10 billion. This emerging challenge will present itself in multiple dimensions, particularly affecting nutritional security among marginalized sectors of society. This situation will require an intervention in the form of a second green revolution. It is important to keep in mind that this revolution must also include sustainability considerations, as resource constraints are increasing daily. The focus on micronutrients should not only be from a scientific research standpoint but also necessitates policy interventions that promote their use while discouraging N P K consumption. Nutrient-based subsidies and soil health cards have been examples of such interventions in the past that have encouraged more rational nutrient use. Micronutrient management is essential for crops, livestock, and human health equally.

Globally, over two billion people are affected by micronutrient deficiencies1. These deficiencies can negatively influence learning, IQ, motor skills, and immune system functionality, and children who are deficient in micronutrients may experience enduring effects into their adult years [63,64]. In particular, zinc deficiency was estimated to have led to 116,000 deaths among children under five years old worldwide in 20114. Additionally, it is anticipated that by 2050, 175 million more individuals may become zinc deficient due to the rising levels of CO2 globally [65]. In the developing world, a considerable segment of the population is potentially at an increased risk for mineral deficiencies because they consume crops that are grown in soils with low bioavailable mineral concentrations. The low availability of minerals in the soil results in many cereals, legumes, and vegetables having insufficient mineral levels [66] and the application of mineral-enriched fertilizers could help mitigate this issue [67]. As a result, several nations, including Finland, China, and Turkey, have adopted agronomic fortification—enhancing fertilizers or irrigation water with trace minerals such as selenium, iodine, and zinc—in what appear to be successful initiatives to improve crop mineral levels and the mineral status of the domestic population [68,69].

According to Bevis et al. (2023), there is a correlation between child stunting and the availability of zinc in the soil in Nepal's Tarai region, even when various soil, demographic, and environmental characteristics are controlled and More investigation in this field is required to determine to what extend soil quality impacted the nutritional security of the human beings and livestock [70].

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