Micronutrients deficiencies vis-à-vis food and nutritional security of India

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Introduction

It is estimated that by the year 2050, world human population will be 9.7 billion, and India's population is projected to overtake that of China. The population of India will rise to 1.6 billion from its current level of 1.2 billion. Skewed use of major fertilizer nutrients without micronutrients is a prime concern for achieving the agricultural intensification required to feed the growing world population with nutritious food. A challenge for Agricultural scientists is to feed the world population with nourishing food. The issue of micronutrients deficiency is related with food and nutritional security. Micronutrients are major limitations across the world and controls crop productivity as well as produce quality (especially micronutrients concentration). Micronutrients deficiencies are difficult to diagnose and consequently the problem is termed 'hidden hunger' (Stein et al., 2008). Pressure on a fixed land base to produce more food has driven a shift in production toward cereals. Cereals are generally low in micronutrients compared to many other food crops and growing them on micronutrients deficient soils further reduces their concentration in these crops. Indian diets mainly consist of cereals like, rice and wheat, which are inherently low in micronutrients, and thus it raised concern for animal and human health.

Research efforts that relate micronutrient deficiency in soils with human health and its remediation are only at infancy in India. Zinc deficiency in human diet was reported as early as 1961 and expressed its syndrome as hypogonadism, dwarfism, hepatosplenomegaly, anaemia and geophagia (Singh, 2008). The research work on micronutrients in soil and its impact on animal/human health is very limited despite the obvious connection between soil micronutrients status and human health known since time immemorial. Today, most agricultural systems in the developing world do not provide enough nutrients. Many fall short of supplying enough micronutrients (14 trace elements and 13 vitamins) to meet human needs, even though the production of energy and protein via cereal crops appears to be adequate to feed the world.

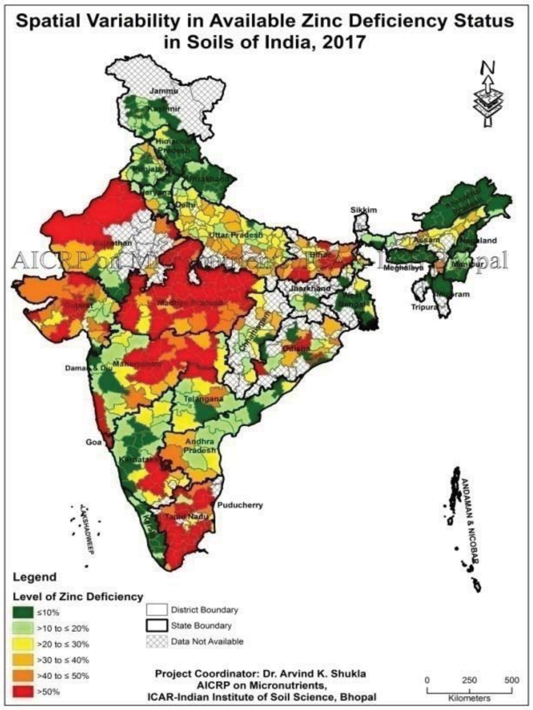
In order to understand the relationship between micronutrient supply and human health there is immense need to understand level of micronutrients deficiencies in soils. Micronutrients distributions in soils are not often completely independent of each other. Some elements are related to parent materials, and these relations may persist in soils. Availability can be defined as the quantity of a soil nutrient that is accessible to plant roots over some useful period such as a growing season. Because plant roots accumulate micronutrients directly from the soil solution, the total pool of soil micronutrients is not directly available. The distribution of available micronutrients is governed by exchange phase, chelated with or contained in organic matter, adsorbed or fixed on clays, adsorbed or occluded in or on oxide minerals or carbonates, or be constituents of residual primary minerals. The information pertaining to distribution of available micronutrients including multiple micronutrients deficiencies is immensely needed to established link between soil and available micronutrients and human health.

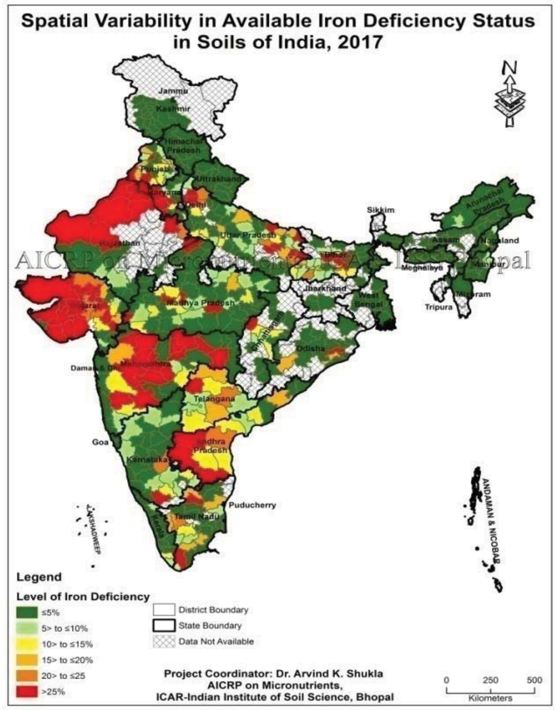
Mapping micronutrients deficiency in Indian soils

In spite of the relatively high total concentrations of micronutrients reported in soils of India, micronutrient deficiencies have been frequently reported in many crops grown on various soils of the country due low levels of available micronutrients in soils. Availability can be defined as the quantity of a soil nutrient that is accessible to plant roots during the period of growing season. Since plant roots accumulate micronutrients directly from the soil solution, the total pool of soil micronutrients is not directly available. Based on the critical limits followed in different states of India the micronutrients deficiency status has been assessed in different soils during 2011-2017. The analysis of more than 2.0 lakhs soil samples during 2011-2017 revealed wide spread micronutrients deficiency in soils. On average, 36.5, 12.8, 4.2, 7.1 and 23.2% soils are deficient in Zn, Fe, Cu, Mn and B, respectively (Shukla and Behera, 2017).

In order to formulate the remediation strategies for the correcting micronutrients deficiencies in crops, GPS based district-wise micronutrients delineation programme has been performed during 2011-17 and PSD maps have been prepared by ICAR-AICRP-MSPE in various states of India. The DTPA-extractable Zn in Indian soils ranges from 0.01 to 52.9 mg kg^{-1} and it constitutes less than 1% of the total Zn content. Currently 36.5 % of soil samples across the country are deficient in available Zn. The Zn deficiency varied among states with a minimum of 9.6% in Uttarakhand to as high as 75.3% in Rajasthan (Map 1). By and large, Zn deficiency was higher in the states of Madhya Pradesh (66.9%), Tamil Nadu (65.5%), Maharashtra (54.0%), Bihar (44.0 %), Uttar Pradesh (33.1%) and 9.6 to 25% in other states (Map 1). The most Zn deficient soils are the ones that are coarser in texture (sandy/ loamy sand), high in pH (> 8.5 or alkali/ sodic soils) and or low in organic carbon (< 0.4%), or calcareous/ high in $CaCO_3$ (> 0.5%) and intensively cultivated (Shukla et al., 2014). In India, the problem of iron deficiency is mainly in calcareous and other alkaline soils having pH > 7.5. The availability of Fe gets reduced under draught or moisture stress condition due to conversion of ferrous form of iron (Fe^{2+}) into less available ferric form (Fe^{3+}). Sometimes, high concentrations of P, NO_3-N and high organic matter contents also restrict better iron availability to plants. Analysis of more than 2.00 lakhs soil samples in 508 districts of India revealed that 290 districts were having very high Fe content, particularly in acid and waterlogged soils (Map 2). In India, B deficiency has been recognised next to Zn. Availability B to plants is governed by soil pH, $CaCO_3$ and organic matter contents, beside total B content in soil, interactions with other nutrients, plant type or variety and environmental factors. The concentrations of total B content ranges from 2.60 to 630 mg kg^{-1} (Takkar, 2011) and available (hot water soluble – HWS) B in Indian soils ranged from 0.04 to 250 mg B kg^{-1} with an average of 21.9 mg kg^{-1} soil (Shukla and Tiwari, 2016). Boron deficiency in some region of Indian soils is becoming a serious constraint to sustainable agricultural productivity. By and large, B deficiency is more critical to sustainable productivity in highly calcareous soils, sandy leached soils, limed acid soils or reclaimed yellow or lateritic soils. In general, B deficiency was higher in eastern region of the country and has resulted due to its excess leaching in sandy loam soils, alluvial and loess deposits (Takkar, 1996; Shukla and Behera, 2012; Shukla and Tiwari, 2016). Recent analysis of soils across 508 districts revealed that B deficiency is more common in highly calcareous soils of Bihar and Gujarat and acid soils of West Bengal, Odisha and Jharkhand .

Total Mo in Indian soils ranges between 0.1 to 12 mg kg^{-1} and available Mo, extracted with ammonium oxalate (pH 3.3) ranged from traces to 2.8 mg kg^{-1} (Behera et al., 2011; Behera et al., 2014). Molybdate anions (MoO_4^{2-}) are strongly adsorbed by soil minerals and colloids (at pH < 6.0) and sometimes also trapped due to formation of secondary minerals. Hydrous aluminium silicates may also fix Mo strongly. Most of the soils are adequate in Mo but its deficiency is noticed in some acidic, sandy and leached soils. Its deficiency is rarely reported in calcareous alkaline soils of arid and semi-arid regions as these soils have high available Mo contents. Mo deficiency is very scarce and localized in some parts of Maharashtra and acidic soils of Odisha and West Bengal, Kerala and Himachal Pradesh.





Map 1. Zinc deficiency ststus in soils of India Map 2. Iron deficiency ststus in soils of India

Over the years multi-micro and secondary nutrients deficiencies have emerged in different areas of the country. Presently, an average of 9.9, 8.3, 6.2, 5.8, 3.7, 3.3, 2.8 and 2.4% samples were found to be deficient in S+Zn, Zn+B, S+B, Zn+Fe, S+Fe, Zn+Mn, Zn+Cu and Fe+B nutrient combinations respectively. Three nutrient deficiencies like S+Zn+B, S+Zn+Fe and Zn+Fe+B were recorded in about 2.5, 1.9 and 1.1% soils respectively.

Food and nutritional security through micronutrients

Agriculture provides the nutrients essential for human life. The reality of this is hidden when we use the less definitive term "food"; food may or may not provide all the necessary nutrients. We have produced adequate food but not attained the food security. In fact, concept of food security is much different than availability of adequate food. Food security is situation that exist when all people, at all time, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preference for an active and healthy life (FAO, 2011). Whether present agriculture provide adequate amounts of foods containing enough nutrients in balance to meet human needs is a question mark. Thus, providing enough food does not necessarily mean that the food produced will supply enough of all the nutrients needed to support good health. This appears to be the case for the agricultural systems fostered during the ‘green revolution’. Indian population is mostly fed upon rice and wheat cereals. While whole cereal grains provide enough carbohydrates (calorie) and protein to stave off famine, they do not provide enough of all the utilizable micronutrients needed to sustain life, being very low in bioavailable amount of micronutrients (especially Zn and Fe) compared to other staple food crops, like pulse. Health perspective has rarely been studied for many of the elements that are required for human health come from the soil through either plant or animal product elements may also be required directly through the consumption of soils.

Micronutrients deficiencies is a growing concern in the India, resulting in low productivity and poor nutritional quality of produce, which in turn causing diverse health problems in human being, such as stunted growth in children, mental retardations, impairments of the immune system, rickets, osteoporosis, muscular dystrophy and overall poor health. Tackling micronutrient malnutrition in humans is the priority. To a question “If you had 75 billion dollars to improve the world, how would you best spend it?” a panel of ten distinguished economists of the world, who had met to ponder over urgent global challenges facing the world, raised at Copenhagen Consensus, 2008 unanimously answered, “Reduce micronutrient malnutrition”. Problem of micronutrient malnutrition was categorically emphasized because more than half of the humanity - mostly the poor in developing countries - suffers from the devastating consequences of micronutrient malnutrition. No other problem of this magnitude is afflicting such a huge portion of the world population. According to WHO (2002), deficiencies of zinc and iron occupy 5th and 6th place, respectively among top ten leading causes of illness and diseases in low income countries.

Contribution of micronutrients to food crop production of India

Increasing trend in consumption of micronutrients fertilizer and food grain production of the country as depicted in Fig 1 shows the importance of micronutrients in sustainable food production. As per recent estimate of micronutrients consumption, the use of $ZnSO_4$ fertilizer was the highest (1,88,305 tonnes) followed by iron sulphate (21,188 tonnes), boric acid/borax

(19,976 tonnes), manganese sulphate (2,740 tonnes) and copper sulphate (1,369) during 2015-16. Of the total Zn used, 70% goes to the field crops and remaining 30% to vegetable and fruit crops, while the reverse is true for Mn, Fe and Cu. Of the total B application, about 60% are applied to vegetables and fruit crops and 40 % to food and oilseed crops (Shukla et al, 2012). According to an estimate, the contribution of Zn and B fertilizer to present food crop production comes around 29 Mt rice equivalent yields (Shukla and Behera, 2011; Shukla et al, 2012). The contribution from other micronutrients should not be underestimated as their use has been increasing consistently and enhancing crop productivity.

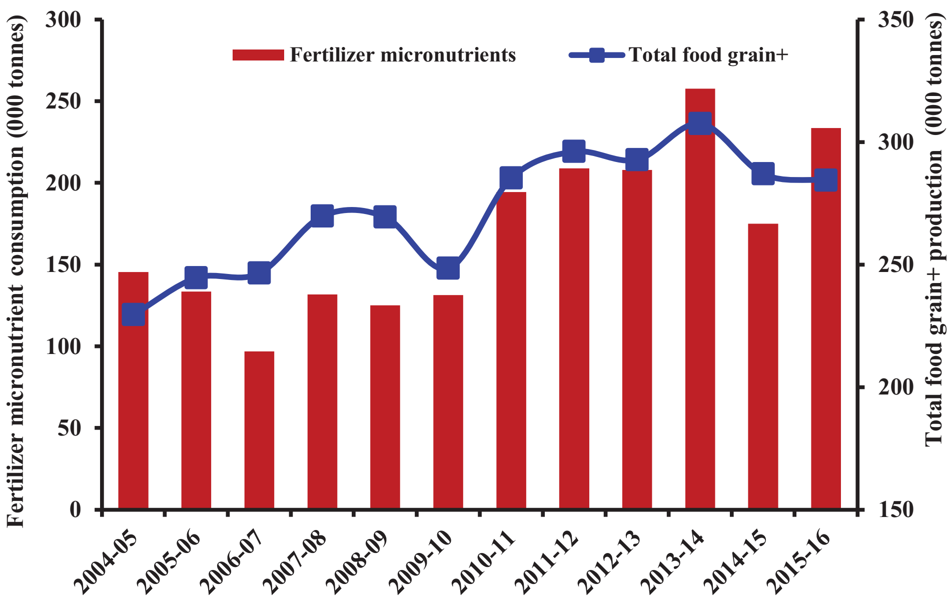


Fig 1. Micronutrient fertilizer consumption vis-a-vis food grain production in the country during last decade

Economic well-being and micronutrients access

Though the economic theory predicts that with increased income, individuals should be able to purchase more food and diversify their diets, especially with animal products, thereby improving their micronutrient status. But this does not appear to be the case. For example, in Asia the availability of iron in food has declined even though income and the availability and intake of foods containing high amounts of energy (i.e., cereals) have risen significantly. At the same time, iron deficiency in women, infants, and children in resource-poor families has risen dramatically. Indeed, in South East Asia, iron deficiency now afflicts 98.2 % (over 1.4 billion) of the people in that region. Within the developing world, serious vitamin and trace element deficiencies persist and are not necessarily corrected by increased income within an acceptable period of time. Study conducted in India revealed that widespread deficiencies of Zn in Indian soils and crops, low Zn concentrations were found particularly in the diabetic and diabetic-ulcer patients than normal surgical patients without metabolic diseases, however, most of the diabetic patients were richer than normal population (Sheshadri, 1998). Similarly, prevalence of anaemia particularly in women was reported across the country; although there is no strong relationship between iron availability in soil, economic status of people and occurrence of iron anaemia in some cases (Singh, 2008). The Zn deficiency in human population is wide spread in India (Brevik, 2010) however, economic well-being has improved in last decade. Though micronutrients are needed in small quantities (i.e., micrograms to milligrams per day), they have incredible impact on human health and well-being. Insufficient dietary intakes of these nutrients impair the functions of the brain, the immune and reproductive systems and energy metabolism. These deficiencies result in learning disabilities, reduced work capacity, serious illnesses, and death. Micronutrient malnutrition is a serious global affliction that limits the work capacity of people and seriously hinders economic development. Dysfunction of the food system from low micronutrient output is affecting more people every day, for examples global trends in iron deficiency anaemia. Agricultural systems must increase micronutrient outputs as a primary tool to eliminate micronutrient malnutrition (Welch, 1995). Finding sustainable solutions to this developing global nutrition crisis will not be possible without the cooperation of agriculture.

Linking soil micronutrients and human health

Soils seriously deficient in minerals cannot produce plant life competent to maintain our needs and with the continuous cropping and shipping away of those concentrates the condition become worse. Nobel Prize winner, Dr. Alexis Carrel stated that minerals in the soil control the metabolism of plants, animals and man. Accordingly, life will be either healthy or unhealthy depending upon plant available nutrients in the soil. Due to rampant deficiency of micronutrients in agricultural soils, food grown in these soils lack in the amount of nutrients needed to maintain human health. Zinc deficiency is a well-recognized micronutrient deficiency problem both in human populations and in crop production globally. It is estimated that nearly half of the soils on which food crops are grown, are deficient in plant available Zn, leading to reductions in crop production and also nutritional quality of the harvested grains. Since cereal grains/seeds contain inherently very low amount of Zn, growing them on potentially Zn-deficient soils further decreases grain Zn concentrations. Since cereal-based foods (Rice and wheat) are the major source of daily calorie intake hence widespread occurrence of Zn deficiency reported in human populations in India. Studies conducted under All India Micronutrient Project in Nalgonda and Ranga Reddy districts in Andhra Pradesh indicated that soils having low zinc status produced plant, grains with lower zinc content. People feeding on such grains and other vegetation showed lower zinc content in their blood plasma compared to areas which had high available zinc status and lower zinc deficiency in soil (Singh, 2008). Severe iron anaemia was found in 34% in adolescent girls of Bikaner, Rajasthan and Gujarat. The concentration of Zn, Cu, Fe and Mn in drinking water and soil is correlated with dental caries in 1516 children (7 to 17 years age) in 10 rural areas in the district of Ludhiana (Graham et al., 2001). There is an urgent need to replenish the nutrient in topsoil and increase the nutritional values of harvested food to sustain human health. Crops require minerals and organic materials to transform nutrients into forms that plants can use for growth. Without minerals and soil organic matter it is impossible to sustain a healthy crop which is the basis for the nutrition values of animals and human. Unless growers replenish nutrients, the mineral content of harvested food will continue to decrease. The decline in nutritional quality of food has been linked to soil degradation or the “mining” of soil fertility. Along with losing the ability to hold nutrients, the bio-availability of minerals for plant growth has been significantly decreased as a result of the accelerated withdrawal of minerals from the soil without corresponding additions has severely impacted on human health.

Approaches to ensure nutritional security

Both research and developmental issues related to malnutrition need to be addressed to attain the nutritional security of the people. There are several approaches like dietary diversification, mineral supplementation and food fortification may be helpful in combating micronutrients malnutrition. But, these programs have treated the symptoms of micronutrient malnutrition rather than the underlying causes. While many of these interventions have been successful in the short term for the individuals reached by them, they have proved to be unsustainable and incapable of reaching all the people affected. Indeed, they are least likely to reach those most at risk, namely resource-poor women, infants, and children that live in remote areas either far from a clinic or those who do not have ready access to processed and fortified foods. In spite of these interventions, the problem continues to increase.

To address micronutrient deficiencies in the comprehensive way, several approaches are needed simultaneously. The development of new food systems to deliver the required nutrients sustainably may be possible research solution to combat micronutrients deficiency in human by enriching the crops produce with micronutrients though biofortification (Borkakati and Takkar, 2000). Therefore, even when socio-economic factors make it difficult to change the diet, the nutrient balance of cropping systems where cereals figure prominently can be improved.

Strategies to enhance nutritional (Zn and Fe) quality of edible plant parts:

Biofortification

Enrichment of crops with micronutrients is the best option for elevating micronutrients concentration in food crops, especially in cereals. This can be achieved either by breeding crop cultivars that absorb and transmit more micronutrients to grains or by fertilizing crops with micronutrients. Breeding crop cultivars for micronutrient enriched genotype is time taking process whereas fertilizing crops with micronutrient is easy and convenient and it takes less time. Although the total concentrations of Fe, Zn and Cu in most soils are sufficient to support mineral-dense crops, the accumulation of these mineral elements is often limited by their phyto-availability and acquisition by plant roots. The concentrations of mineral elements in edible crops can be increased by the judicious application of mineral fertilizers and/or by cultivating genotypes with higher concentrations. The bioavailability of mineral elements can also be increased through crop husbandry, breeding or genetic manipulation. Biofortification focuses on enhancing the mineral nutritional qualities of crops *at source,* which encompasses processes that increase both mineral levels and their bioavailability in the edible part of staple crops. The former can be achieved by agronomic intervention, plant breeding or genetic engineering, whereas only plant breeding and genetic engineering can influence mineral bioavailability.

i. Genetic biofortification

Although genetic biofortification is a powerful and sustainable strategy but it is long-term process requiring series of breeding activities and huge resources. Moreover, it is difficult to ascertain that cultivar developed after long time will be sustainable in soils further mined by that time. Most importantly, newly developed genotypes should be able to extract sufficiently large amounts of Zn/Fe from potentially deficient soils and accumulate it in whole grain at sufficient levels for human nutrition. The soils widespread in major cereal-growing regions have several adverse soil chemical factors that could potentially diminish the expression of high grain Zn/Fe trait and limit the capacity of newly developed (biofortified) cultivars to absorb adequate amount of Zn/Fe from soils to contribute to daily Zn/Fe requirement of human beings.

ii. Agronomic manipulation

Agronomic manipulation is an inexpensive and simple approach which can be utilized to enrich genetically inefficient cultivars by application of micronutrient fertilizers at different rates, methods and at different crop growth stages (Brevik, 2010; Shukla and Behera, 2012). Fertilizer strategy could be a rapid solution to the problem and can be considered an important complementary approach to the on-going breeding programs. Fertilizer studies focusing specifically on increasing Zn concentration of grain (or other edible parts) are, however, very rare, although a large number of studies are available on the role of soil and foliar applied Zn fertilizers in correction of Zn deficiency and increasing plant growth and yield. In India, through NAIP funded project on micronutrients enrichments, efforts have been made to identify genetically efficient cultivars of cereals and pulses for Zn and Fe to develop options for micronutrients biofortification. Genetically efficient and inefficient cultivars were identified based on Yield Efficiency and Uptake Efficiency Index. Interestingly, the genetically inefficient cultivars were agronomically highly efficient. Thus, the efficient cultivars could be utilized by breeders for QTL identification and developing high yielding micronutrient enriched cultivars (genetic biofortification) while the inefficient cultivars were for agronomic biofortification to dense the grains of highly responsive cultivars with micronutrients.

iii. Physiological manipulation

The physiological basis for micronutrient efficiency in crop plants plays a major role in controlling the accumulation of micronutrients in edible portions of seeds. There are several barriers to overcome in genetically modifying plants to accumulate more micronutrient metals (e.g. Fe and Zn) in edible tissues. It has also been recorded that nipping practice enhanced Fe concentration both in efficient and inefficient cultivars of chickpea and pigeon pea grown at Anand, Gujarat. In chickpea, nipping of apical buds at grand growth stage but before flowering resulted in 11% increase in Fe concentration in grain of efficient cultivars (GG1 and GAG 735) while in inefficient cultivars (ICCC4 and GJG 305) this increase in grain Fe was only 5 per cent. Defoliation (25% of leaves) at pre-flowering stages could enhance the Fe concentration in grain by 7 and 4% respectively in efficient and inefficient cultivars. In case of pigeon pea, nipping and defoliation had greater response than that recorded in chickpea. The grain Fe concentration had increased by 17 and 5% in efficient (BDN-2 and PKV Trombay) cultivars after nipping and defoliation, while in inefficient cultivars (C-11 and AAUT 2007-08) the increase was reckoned by 10 and 12 percent, respectively.

Micronutrients enrichment *vs.* Antinutrients

Application of micronutrients have not only influenced the micronutrients concentration in edible plant parts but also affected nutrients and antinutrients content, particularly phytate and methionine. Since Zn supply to crop improved the protein concentration in cereals, hence, methionine concentration also increased with Zn management. Zinc application has increased methionine level more in inefficient cultivars than that efficient cultivars. Although, phytate concentration and antinutrients also increased with application of micronutrients, however, phytate: Zn ratio decreased significantly due to excess Zn absorption in crops supplied with external Zn through soil and/ or foliar feeding. The phytic acid content in different wheat genotypes decreased with increasing levels of Zn with the lowest values obtained when nourished with 20 kg Zn SO_4 ha^{-1} + foliar spray. The greater P uptake under reduced Zn supply or reduced P uptake with increased Zn nutrition may be absorbed between both the elements for the same site of absorption in roots. Due to enhanced grain Zn content with Zn application the phytate to Zn molar ratio exhibited a progressive reduction with increasing levels of zinc. The foliar feeding along with soil application is the best Zn management option to get lowest phytate: Zn ratio. Potassium fertilization along with Zn further enhanced Zn accumulation and thereby reduced phytate: Zn ratio in seed. Similar to wheat, methionine content in pigeon pea increased with increasing levels of Zn. The K fertilization along with Zn further enhanced the methionine content in grain. Due to sizable accumulation of Zn in grains, the phytate Zn ratio also reduced.

Bio-assimilation of enriched cereal and pulse grains

Once the grains are enriched with micronutrients (Zn/Fe) bioavailability was assessed using rat models. The results revealed that Zn intake was more from pigeon pea, wheat based diet and the highest from seeds of inefficient cultivars that contain high Zn. The excretion of Zn/Fe was also higher in rats fed with Zn/Fe enriched grain due to excess intake but Zn/Fe supplied through enriched grain was bioavailable to animals as good as Zn/Fe supplied through standard sources. Fe/Zn concentration in different body parts of rats, liver, kidney and femur where comparable in all treatments but total absorption was high from wheat based diet because of its greater intake by rats. When rats were fed with Zn/Fe deficient diet, it had effect on kidney, liver and haemoglobin content.

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