PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–17
https://doi.org/10.14719/pst.5759

HORIZON
e-Publishing Group
HePG

REVIEW ARTICLE

Nutrient nexus: Linking soil, plants, animals and humans

M Soorya[1], S Suganya*[1], M Elayarajan[1], V Davamani[2], P Chitra[3]

[1] Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Environmental Science, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: suganssac2010@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 14 October 2024
Accepted: 10 November 2024
Available online
Version 1.0 : 31 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Soorya M, Suganya S, Elayarajan M, Davamani V, Chitra P. Nutrient nexus: Linking soil, plants, animals and humans. Plant Science Today.2024;11(sp4):01-17. https://doi.org/10.14719/pst.5759

Abstract

The complex interrelationships between soil, plants, animals, and humans form the nutrient nexus, where the health and well-being of each component are intricately linked. This article comprehensively explores the dynamics of nutrients through this continuum, emphasizing the vital role of nutrient management in ensuring food security, sustainable agriculture, and a balanced ecosystem. It delves into the importance of nutrients at various levels, investigating case studies that illustrate the correlation between soil nutrient availability, plant uptake, animal nutrition, and human health. The article also examines government initiatives, nutrient management practices, and strategies like dietary diversification, biofortification, food fortification, and supplementation to combat nutrient deficiencies. The integration of traditional knowledge with modern scientific advancements advocates for a holistic approach to nutrient management, considering local resources, cultural practices, and environmental conditions.Ultimately, the article highlights the necessity of efficient nutrient management not only for ensuring food security but also for preserving the delicate balance of our planet's ecosystems for future generations.

Keywords

food security; government policies; nutrient management; nutrient nexus; soil health; soil-plant-animal-human nutrition; sustainable agriculture

Introduction

The relationship between soil, plants, animals, and humans is complex and interdependent, relying on many factors such as microbial community and their interactions with other organisms, habitat, abiotic factors that include climate, agricultural practices, pesticide use, etc (1). Soil is the primary source of nutrients. Humans who consume a diet based on plants cultivated in nutrient-deficient soils suffer from nutrient shortage, which affects their well-being, child survival, and life expectancy (2). This issue not only affects humans but also impacts animal health. The importance of the Nutrient Nexus arises because of this interconnection, a cycle in which soil promotes plant growth, plants support livestock, and both support human well-being through food production and ecosystem services (3). The vitality of all beings depends on the health of the soil. If the soil is contaminated or deficient in any one of the nutrients, it is going to be affected from primary producers to tertiary consumers of the food chain. Additionally, the soil is home to millions of organisms that directly or indirectly impact life on the land's surface. Thus, all living beings are interconnected under a single system, in which changes in one factor affect the others due to their interconnectedness (4). The importance of the Nutrient Nexus is depicted in (Fig. 1).

Soil health is interlinked with soil quality. Soil quality is defined as "the capacity of soil to perform in an ecosystem to sustain biological productivity, maintain environmental quality, and promote the health of animals and humans" (5). Also, the multifunctional system of soil can be defined as "the capacity of the soil to promote the growth of plants, protect watersheds by regulating the infiltration and partitioning of precipitation, and prevent water and air pollution by buffering potential pollutants such as agricultural chemicals, organic wastes, and industrial chemicals" (6). Microorganisms play an important role in monitoring soil health. They improve the structure of soil by binding particles together through the release of organic molecules, specifically sugars. Microbial activity has an impact on soil physical qualities such as water retention, infiltration rate, resilience to erosion, and compaction susceptibility. Microbes create extracellular polysaccharides and cellular waste, which help to stabilize and improve soil health, thereby increasing nutrient availability. Notably, variations in microbial populations or activity suggest early signs of soil improvement or degradation (7).

Sir Albert Howard, a pioneering figure in agricultural techniques, asserted that "The real arsenal of democracy is a fertile soil, the fresh produce of which is the birthright of nations." This underscores the idea that the fertility of the soil is a non-renewable resource that cannot be replenished easily after its destruction. The growth of a kingdom in the past and a nation in the present significantly depends upon the fertility of the soil (8). Fertile soil is a valuable resource that can amplify plant growth, thereby linking the legitimate growth of animals and humans. In conjunction with the One Health concept, soil health is interlinked with the health of the plant-animal-human continuum and the health of the planet. Recent developments have incorporated socio-economic, cultural, and ecological factors into One Health; however, biological aspects remain the core focus. The One Health concept recognizes that the health of all organisms is interconnected via microbial communities that cycle between soil, plants, animals, and humans, influencing the general health of ecosystems. This microbial interaction, which occurs over time and space, is critical to preserving ecological balance and health (9).

Fig. 1. Nutrient nexus: linking soil, plants, animals, and humans.

It is important to note that consuming foods rich in diverse nutrients and low in energy intensity can mitigate various nutritional disorders, lower cellular stress, and increase cellular functions and health (10). Additionally, dietary intake of fruit and rich in fiber and magnesium reduces depression in pregnant women, possibly due to the association with the brain's central nervous system (11). During the recent global COVID-19 pandemic, substantial emphasis was given to nutritious diets containing sufficient nutrients, which, coupled with chronic disease and nutrient deficiency, raised the possibility of severe infection (12). From these, we can conclude that nutrients are important to plants, animals, and humans, and their biotransfer from soil to animals and humans *via* plants represents an important area of study, integrating management practices to increase nutrient content in the food chain**.** The purpose of this article is to explain the interconnected dynamics of soil, plants, animals, and humans within the nutrient nexus, focusing on the significance of nutrients and their management for sustainable agriculture, food security, ecosystem balance, and enhanced health.

Importance of Nutrient Nexus

Nutrients are critical to the health and productivity of soil, plants, animals, and humans. In the soil, they promote plant development, microbial activity, and fertility. Plants require nutrients for photosynthesis, growth, and stress resistance. Animals require proteins, carbohydrates, lipids, vitamins, and minerals to function properly. Humans require a well-balanced nutrient-rich diet for metabolism, immunity, and overall health (13). These systems are interrelated because healthy soil generates nutrient-rich plants, which in turn supply high-quality food for animals and humans, assuring sustainability and food security.

Nutrient nexus in soil

Soil fertility indicates the ability of the soil to supply essential nutrients in sufficient amounts and appropriate ratios for normal growth and development. It can also be defined as the inherent capacity of the soil to supply nutrients to crops in adequate amounts, and suitable proportions, and at an appropriate time when other growth factors such as light, moisture, temperature, and the physical condition of the soil are favorable (14). Soil fertility is a predictor of crop yield and food security. Fertile soils provide essential nutrients to plants, leading to higher crop productivity. Fertilizers are more effective when applied to soils high in organic matter and nutrient concentration. Nutrient-rich plants not only enhance animal nutrition but also contribute to human health. On the other hand, poor soil fertility hampers plant growth, which can reduce the intake of essential minerals by humans, impacting overall well-being (15). Foth & Ellis in 1997 defined fertility as 'the status of a soil concerning its ability to supply elements essential for plant growth without a toxic concentration of any element''.

Plants require 20 essential elements for normal growth and development. The elements such as carbon, hydrogen, and oxygen are supplied through the atmosphere and water. The other elements are obtained by plants either by the mineral composition available in the soil as solid, liquid, and gaseous phases or by being supplied to the plants as amendments. The nutrients that are needed by plants in larger quantities are called macronutrients, which are again classified as primary nutrients (C, H, O, N, P, and K) and secondary nutrients (Ca, Mg, S, Na, and Si). Here, N, P, and K have been widely used as fertilizers since the post-Green Revolution era because they are directly involved in increased crop growth and quality (16). The nutrients needed in smaller quantities are called micronutrients, which include Fe, Mn, Zn, Cu, B, Mo, Cl, Co, and Va. Plants absorb nutrients in various forms from their root systems. Although soil contains many nutrients, only a small quantity is required by plants. For example, soils may contain up to 50,000 ppm of Fe, but plants require less than 5 ppm for optimal growth. The availability of nutrients depends on many factors, such as soil moisture content, aeration, temperature, soil colloids, presence of organic matter, pH (17). The micronutrients are needed in smaller amounts, and their deficiency may lead to adverse effectsin plants, animals, and humans. There are mainly four stages of micronutrient deficiency. In the first three stages, symptoms may not appear prominent, and they fall under the category of hiddenhunger and can only be identified at the time of yield reduction. In the fourth stage, deficiency symptoms may appear (18). Therefore, these twenty nutrients are essential, which fall under Arnon and Stout's (1928) 'Criteria of Essentiality' and are needed by all living beings for proper growth and development. Thus, the management of both macro and micronutrients is equally important (19).

Nutrient nexus in plants

The growth and development of plants is influenced by the supply of nutrients. Plants require a variety of nutrients, which are essentially categorized into macronutrients and micronutrients. Macronutrients are substances that plants require in huge quantities, usually in amounts exceeding one part per million (ppm) while, micronutrients are required in smaller quantities, generally below 1 ppm (20).

Mengel and Kirkby in 1987 suggested a framework for classifying plant nutrients according to their metabolic activities. Plants absorb CO_2, HCO_3^-, H_2O, O_2, NO^{3-}, NH_4^+, N_2, SO_4^{2-}, and SO_2^- as ions from soil solutions or gaseous form from the environment. These elements are from the first group, which are the primary components of organic material. The second group includes phosphorus (P) and boron (B), which share similar biochemical properties. Plants absorb these elements as anions or acids from soil solutions, such as phosphates, boric acid, borate, and silicate. The third group includes potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), manganese (Mn), and chlorine (Cl). These elements carry out nonspecific ionic biological functions such as producing osmotic potential in cell organelles, managing ionic balance, and controlling membrane permeability, electro-potential, and conductivity. The fourth group comprises iron (Fe), copper (Cu), zinc (Zn), and molybdenum (Mo), which are considered chelates incorporated into prosthetic parts in plants. These elements enhance electron transport by changing valency during certain enzyme processes (21).

Nutrients also play a role in disease resistance and plant growth. It is also worth noting that proper nutrition management through fertilization, combined with an integrated pest control system, can greatly reduce the incidence of disease. Nutrient-disease relationships include *Streptomyces* scab of potatoes, *Verticillium* wilt, take-all (*Gaeumannomyces graminis*) of wheat, eyespot (*Pseudocercosporella herpotrichoides*) and sharp eyespot (*Rhizoctonia cerealis*) diseases of wheat, stalk rot of maize, clubroot (*Plasmodiophora brassicae*) of crucifers, and *Fusarium oxysporum* wilt (22). The important nutrient deficiency and toxicity symptoms in plants are tabulated in (Table 1). The visual deficiency symptoms of different crops are visualized in (Fig. 2).

Nutrient nexus in animals

Minerals are required by animals for a variety of functions, including the formation of organ and tissue structures, acting as cofactors or activators in enzymes and hormonal systems, their presence in body fluids and tissues, and the regulation of cell processes such as replication and differentiation. Mineral deficiency, imbalances, and toxicity can harm animal production, particularly in developing nations, sometimes causing more harm than infectious diseases. Deficiencies of certain minerals may lead to reproductive issues since they play a crucial role in the health and reproduction of livestock. Infertility and reproductive disorders have become a significant problem affecting livestock populations (23).

Mineral deficiencies in animals can cause numerous health issues such as stunted growth, decreased appetite, anemia, bone deformities, skin and hair problems, impaired lactation, reproductive dysfunction, and reduced egg production and quality (24). Macronutrients such as calcium (Ca), phosphorus (P), magnesium (Mg), sulfur (S), sodium (Na), potassium (K), and chlorine (Cl) and micronutrients such as manganese (Mn), zinc (Zn), iron (Fe), copper (Cu), selenium (Se), iodine (I), cobalt (Co), and molybdenum (Mo) are essential for animals. Ca and P are the structural components of the animal body which are found in bones, teeth, as well as cellular fluids (1%). Calcium (Ca) plays a role in blood coagulation, enzyme activation, muscle contraction, ion channel regulation, nerve impulse transmission, and membrane permeability. Phosphorus (P) is a key component of ATP, DNA, RNA, and phospholipids, supporting nutrient transport and cellular fluidity. Magnesium (Mg) activates enzymes and is involved in carbohydrate and protein metabolism. Sulfur (S) is

Table 1. Deficiency symptoms (referred from (75) and toxicity symptoms (referred from 76-86) in plants.

Nutrients	Deficiency in Plants	Toxicity in Plants	Reference for toxicity
Nitrogen	Chlorosis, which occurs first on older leaves, disrupts growth, causes early maturity in some plants, and lowers the protein quality of seeds and other vegetative parts.	Delayed maturity, deep green color, lodging, reduced plant growth, lesions on stem and root, and leaf margins rolled downwards.	(76)
Phosphorus	Slow, stunted growth, dark to blue-green leaves, purpling, delayed maturity, and poor seed and fruit development.	Reduction of Fe, Zn, Mn uptake	(76)
Potassium	Chlorosis, or burning in older leaves, slow and stunted development, weak stems, lodging, and reduced seed and fruit output.	Reduction of Ca and Mg uptake, Reduced Boron availability, Decreasedtranslocation from roots to shoots	(77)
Calcium	Brown tips in young leaves. Lack of calcium pectate forms rigid cell walls, causing leaf tearing and stem structure impairment, cupped and crinkled leaves, and terminal bud deterioration.	Coagulative Necrosis, Plasma membrane injury,Cell death	(78)
Magnesium	Older leaves show interveinalchlorosis, turning yellow, golden, or reddish. Corn leaves are yellow with green veins, while potatoes, tomatoes, soybeans, and cabbage have orange-yellow colors. Severe cases may cause immature leaf drop.	Dark colored Vegetation, Stunted growth, Reduction in the uptake of Ca	(79)
Sulfur	Chlorosis on young leaves, inhibited growth rate, and delayed maturity. Rigid, slender, and woody stems resembling nitrogen shortage symptoms.	Acute injury as interveinallesions on broad leaves of plants, Chlorosis	(80)
Zinc	Interveinal chlorosis on young leaves. Banding near the leaf's base. Tiny, mottled,chlorotic new leaves in vegetables. Fruit formation is greatly reduced in citrus. Shortening of internodes and dead tissue drops from interveinalchlorotic leaf patches in legumes.	Curling and rolling of young leaves, stunting of roots, Chlorosis, Death of leaf tips, Inhibit root growth	(81)
Iron	Interveinal chlorosis in immature leaves resulting the appearance of a whitecolor in younger leaves.	Alkagare Type/Akiochi/Bronzing in rice, sugarcane-freckle leaf with stunted root and stem growth, tender, dark brown or purple tobacco leaves, and black spots in the foliage.	(82)
Boron	Inhibited growth in the apical meristem and newly formed leaves, which may thicken and curl. Empty cores in peanuts, black hearts in beets, deformed fruit shapes in papaya, splitting of calyxin carnations, pith in hollow stems in cabbage, broccoli, and cauliflower.	Chlorosis, Necrosis, Brown lesions on leaf surface, Delayed emergence and foliation, Reduction in stem height, dry matter weight, numberof spikes per plant, and yield	(83)
Copper	Trees may experience reduced growth, deformation of young leaves, apical meristem necrosis, and bushy appearance. Bleaching of young leaves,defoliation, and twig dieback in forage grasses.	Chlorosis, Reduced biomass, Inhibition of photosynthesis, and respiration, Reduced lipid content.	(84)
Manganese	Chlorosis with yellow patches in dicots, greenish-grey flecks later turning to goldento yellow-orange in monocots, and marsh spots in legumes.	Marginal chlorosis, leaf necrosis, Puckering, necrotic spots, crinkle leaf, stem streak necrosis, and internal bark necrosis in apple trees. In severe cases, plant roots also turn brown.	(82)
Molybdenum	Aids assimilation of nitrogen leads to chlorosis in older and middle leaves, necrotic patches on leaf margins, stunted plants, and limited flower formation.	Toxicity is extremely rare with mild yellowing, increased anthocyanin concentration and reduced growth ofseedlings	(85)
Chlorine	Plant wilting and chlorosis in young leaves.	Chlorotic leaves, Necrotic leaf edges, Leaf abscission	(86)

essential for the structure of hair, feathers, skin, cartilage, and connective tissue, and is found in compounds like chondroitin sulfate, heparin, insulin, amino acids, thiamine, biotin, and glutathione peroxidase. Sodium (Na), potassium (K), and chloride (Cl) act as electrolytes, regulating pH, osmotic pressure, and cell signaling. Sodium is crucial for muscle contraction and nerve impulses, potassium supports heart functions, and chloride aids in hydrochloric acid (HCl) production for digestion and promotes skeletal growth. Manganese (Mn) is necessary for carbohydrate metabolism, bone formation, and acts as a cofactor in lipid metabolism. Zinc (Zn) is involved in over 100 enzyme functions, insulin synthesis, immunity, and reproductive health. Iron (Fe) is essential for hemoglobin production and functions as a cofactor for enzymes like cytochromes, catalases, and peroxidases. Copper (Cu) supports blood formation, enzymatic processes, and the conversion of tyrosine to melanin pigment. Selenium (Se) is a component of glutathione peroxidase and deiodinase enzymes. Cobalt (Co), found in tissues like the liver and kidneys, is part of Vitamin B12 and aids in volatile fatty acid metabolism. Iodine (I) is a constituent of thyroid hormones, regulating cellular oxidation and basal metabolic rate (BMR). Molybdenum (Mo) acts as a cofactor for xanthine oxidase and nitrogenase enzymes. Chromium (Cr) plays a role in glucose metabolism, enhances immunity, and reduces respiratory problems in cattle. Chromium is added to swine feed to enhance metabolic efficiency, promoting lean muscle growth by redirecting energy from fat storage, thereby reducing carcass fat (25). Even though the elements are essential to animals for their normal growth,

Fig. 2. Visuals showing deficiency symptoms of various nutrients in field crops, fruits, and vegetables (referred from 96).

the imbalanced intake of dietary nutrients can lead to deficiency or toxicity and cause several problems which are listed in (Table 2).

Nutrient nexus in humans

Mineral nutrients are essential for human health and are often regarded as even more important than vitamins. Growing horticultural crops and vegetables in nutrient-deficient areas, continuous cropping, and pollution are key causes of nutrient imbalance. Continuous cropping involves persistent agronomic practices such as tillage, fertilization, pesticide use, irrigation, and farm machinery, which drive the evolution of certain weeds, pests, and soil pollution. Over time, these practices lead to physio-chemical changes in the soil, including shifts in pH, soil structure, and nutrient balance, ultimately degrading the soil and depleting essential nutrients (26). Nutrients get transferred from animals to the human system via plants. An example is the dietary intake of milk. Milk contains the mineral Ca, and along with Vitamin D, it can increase bone mineral density between the ages of 20 and 30, resulting in reduced chances of bone fracture in old age. Consuming milk as part of a diet can reduce the chances of getting osteoporosis later. Milk and other dairy products also contain other minerals like potassium, phosphorus, magnesium, zinc, manganese, copper, among others (27). Studies have demonstrated that animals fed with fodder that has a high nutrient concentration, like calcium, will have a high Ca concentration in their milk. Moreover, Ca has a strong interrelationship with the soil-plant-animal

Table 2. Deficiency and toxicity symptoms in animals, (referred 25, 87)

Nutrients	Deficiency in Animals	Toxicity in Animals
Phosphorus	Depraved appetite, Abnormal chewing, and eating (Pica), Affect egg shell quality, Reduction in bone ash content	Hyperphosphataemia and extensive damage to tissues
Calcium	Eggshell quality reduction, Rickets, Osteomalacia, Osteoporosis. Lameness, fracture, weakness in legs, abnormal gait particularly in cows and sheep along with osteomalacia. Milk fever and parturient paresis are examples of Ca tetany and hypocalcemia in dairy cows. Cage layer fatigue in the hen.	Nutritional secondary hyperparathyroidism, less Zn absorption, Calculi formation in urea.
Magnesium	Grass tetany or wheat grass poisoning, Head retraction, convulsion, staggering, hypersensitive	Diarrhea, cardiorespiratory depression, depressed feed intake, loss of reflux
Sulfur	Weight gain, Reduced wool, and feather growth	Not a practical problem
Sodium Potassium Chlorine	leg abnormalities in poultry, growth retardation, milk fever in dairy cows, acidosis, and alkalosis	Staggering gait, Reduced Mg absorption
Manganese	Perosis or slipped tendon in chicks, crooked calf in young ruminants, lameness, shortening, bowing of legs, and enlarged joints in pigs, sheep, cattle, and goats. Reproductive problems and a decrease in litter size in large animals reduced hatchability in birds.	Induce iron deficiency
Zinc	Parakeratosis or severe dermatitis with dry, scaly, cracked skin with poor feathering poultry in birds, Delayed wound healing	Least toxic
Iron	Growth retardation, Anemia	Diarrhea, retarded growth, Metabolic acidosis and even death
Copper	Anemia, Scouring, Skeletal deformity, Aortic rupture, Nervous disorder, Change in coat and hair color pigments	Hemolysis of Red Blood Cells, Liver damage, Death, metallic-green color kidneys, and chocolate-colored blood
Selenium	Nutritional Muscular Dystrophy, Exudative diathesis in chickens, and white muscle disease	Alkali disease with abnormal hoof and hair growth, and breaking of hooves. Acute blind staggers
Cobalt	Reduced appetite, Emaciation, Hypoglycemia, Stunted growth	Unlikely
Iodine	Reduced regulation in basal metabolic rate, reduced growth rate and gonadal activities, Brittle hair and dryness of skin, Reproductive problems, Cretinism in young animals, Goiter	Hyperthyroidism, Increased BMR, Pulse rate, nervousness, and excitability
Molybdenum	Rare	Inhibits Cu absorption
Chromium	Rare	Rare

system (28).

The list of required minerals for plants is similar, but not identical, to that of humans. For instance, humans require selenium (Se) and iodine (I), whereas plants typically do not. Human populations that rely on locally cultivated plants may face shortages of these elements due to low soil concentrations. Selenium and iodine deficiencies are common in many parts of the world. While plant-based diets naturally contain nutrients needed by both plants and animals, human may still experience deficiencies in certain minerals. In some cases, mineral concentrations in plants may be insufficient to meet human needs or may exist in forms that are not easily utilized by humans (29).

Currently, scientists are more focused on fortification methods, which include agronomic biofortification, food biofortification, and the use of genetic engineering mainly for the enrichment of minerals like Zn, Fe, Se, I, and Ca, which are considered the limiting nutrients in plant-based food sources (30). The toxicity and deficiency symptoms of different nutrients in humans are listed in (Table 3). So, it is necessary to have nutrient-enriched plant and animal food sources for creating a healthy society which is possible through different management practices like fortification, which is done at the basic soil and plant levels.

Nutrient Interconnections

One of the reasons for the significance of nutrient management is the population explosion. The current population of India is 1.2 billion, and it is expected to rise to 1.4 billion by 2025 and 9.6 billion by 2050. As a result, there is a need to produce all the necessary materials to sustain human life. The most important raw material of these will be agricultural produce itself. By 2025, the country needs to produce at least 300 million tonnes (Mt) of food grains to sustain the human population (31). Since 1950 food grain production has significantly increased due to the adoption of various agricultural practices. However, this growth has come at the cost of soil erosion, nutrient depletion, and soil health deterioration (32).

Maintenance of soil fertility will be one of the key factors in improving crop production without damaging the surrounding environment. This indicates that nutrients lost from the soil solution because of plant uptake, erosion, or any other factors should be replenished by adding nutrients to the soil. The output loss of nutrients

Table 3. Deficiency and toxicity symptoms in humans (referred 88-95)

Mineral	Deficiency in human	Toxicity in human
Iron	Hypochromic microcytic anemia, Reduced cognitive development, low birth weight, maternal anemia, puerperal sepsis, preterm birth	Constipation, Gastrointestinal problems, Organ damage
Zinc	Growth retardation, Idiopathic primary osteoporosis, Hair loss, Dermatitis, Sensory dysfunctions	Nausea, Vomiting, Impair immunity
Iodine	Reduced growth, motor skills, and cognitive development, perinatal mortality, mental retardation, cretinism, Goiter	Impaired thyroid gland
Selenium	Mortality, Cardiomyopathy (Keshan disease), Reduced immune cell count	Selenosis, Hair and Nail loss, Brittleness, Skin rashes, Foul breath odor
Calcium	Rickets, Osteoporosis, Stroke, Hypertension, Pre-eclampsia	Nephrolithiasis (Kidney stone), Constipation
Magnesium	Anorexia, Muscle weakness, Lethargy, Pre-eclampsia	Diarrhea, Abdominal cramps, Nausea, Weakened kidney function
Fluorine	Tooth decay, Cardiovascular disease, Brittle bones	Streaky teeth, Stiffness and joint pain, Skeletal fluorosis
Sodium	Nausea, Diarrhea, Vomiting, Dizziness, Muscle weakness	hypertension, kidney damage, stroke, obesity, cardiac arrhythmias, thrombosis, migraine, tinnitus, Bell's palsy, multiple sclerosis, systemic sclerosis, Hyponatremia
Potassium	Muscle cramps, weakness, loss of appetite, hypokalemia, cardiac arrhythmia	Hyperkalemia, Heart attack, Death
Phosphorus	Anemia, Abnormal White blood cells, Weakened immunity	Affects Calcium homeostasis
Manganese	Rare	Damage in the central nervous system, Hepatotoxicity, Pulmonary Toxicity
Chromium	Decreased insulin sensitivity, increased chances of diabetes	Dermatitis, Skin ulcer, kidney and liver damage, Cancer
Copper	Secondary iron deficiency, Malformations, and immunological abnormalities in the fetus	Gastrointestinal disease, Vomiting, Nausea, Diarrhea, Coma, Death
Molybdenum	Mouth and gum disorders	Relatively low
Nickel	Rare	Bronchitis, Lung cancer, Parakeratosis
Sulfur	Tendinitis, arthritis, bursitis, muscle and joint stiffness, spondylitis, fibrosis, sclerosis	Hormone disruption
Vanadium	No case was found in humans.	Liver or Kidney damage, diarrhea, green tongues, hematological changes, lowered cysteine content in hair and nails

should be in equilibrium with the input addition of nutrients to the soil. The concept of nutrient mining comes from this idea. It is when the amount of nutrients removed from the soil surpasses the amount of nutrients recovered or recycled in the soil. Due to this, there is a chance of reducing soil fertility, and adversity affects the food security of the nation. Even though nutrient mining is a severe problem, the knowledge is limited to the scientific community and has not been effectively communicated to farming systems or practical expertise (8).

To effectively manage and sustain nutrients in the environment, it is essential to understand nutrient dynamics and the factors affecting them. The nutrient flow in the Soil-Plant-Animal-Human Continuum is illustrated in (Fig. 3). Soils provide major nutrients to plants that will regulate the growth of plants according to nutrient availability. Major factors such as pH, cation exchange capacity, organic carbon, and electrical conductivity determine the availability of nutrients, and soil may serve as the major diagnostic tool for nutrient availability to plants (33). The quantity of nutrients present in the soil depends on the nature of the parent material coupled with climatic factors and vegetation. Although the essentiality of nutrients is immeasurable, sometimes the availability may turn into toxicity due to pollution, over-fertilizer application, or geochemical processes (34). Proper nutrient management in the soil exists only when soil health and quality are maintained. As we know, improper

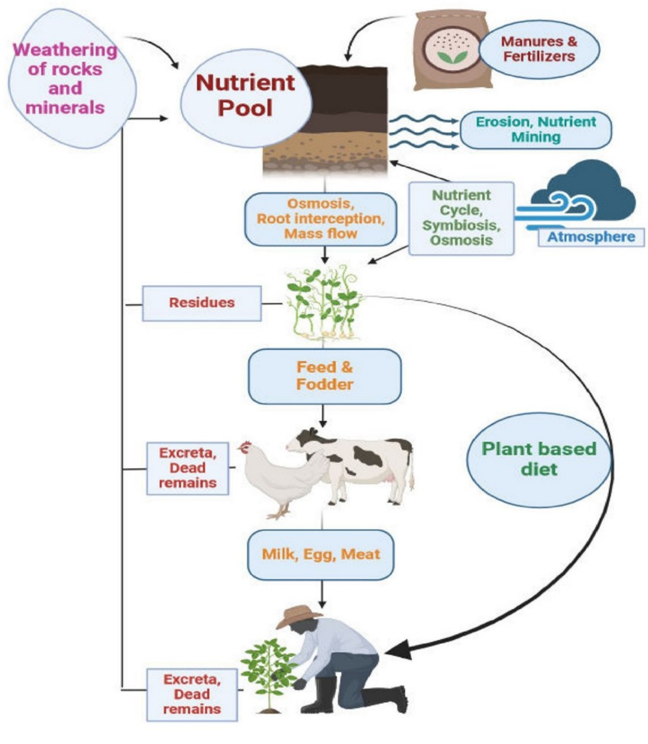

Fig. 3. Nutrient flow in soil-plant-animal-human continuums.

use of fertilizers leads to the overexploitation of nutrients from the soil, ultimately deteriorating its health. The importance of 4R stewardship, 'Right Source, Time, Rate, and Place of Fertilizer Application is projected under this scenario. The objective of this framework is to manage the application of fertilizers that align with social, economic, and environmental sustainability. It considers key factors such as soil, climate, crops, management systems, and logistics when selecting fertilizer Best Management Practices (BMPs) for individual farms. It also connects scientific experts and practical farm implementers to promote efficient and cost-effective practices (35).

Nutrient interconnection case studies

Numerous studies were conducted across India under the All India Coordinated Project on Micronutrients and the National Agricultural Innovation Project (NAIP) to investigate nutrient accumulation and its effects throughout the food chain, from soil to plants to animals and humans. The goal was to assess the health of the environment and society by utilizing proper management practices at different levels of the food chain. Asystematic study was conducted under the AICRP Project at Tamil Nadu Agricultural University in 2013 to assess the relationship between within the soil-plant-animal-continuum (36). Another study was conducted in Coimbatore, Tamil Nadu, based on the transfer of nutrients in various levels of the food chain and yield variation due to different treatments (37). To evaluate the relationship within the soil-plant-animal/human continuum, a study was conducted jointly by the All India Coordinated Research Project on Micro- and Secondary-Nutrients and Pollutant Elements in Soils and Plants (AICRP-MSPE) and AIIMS, Bhopal, covering two tribal districts in Madhya Pradesh. The study involved a systematic analysis of soil,feed, food, and plant samples collected from households participating in the study (18). Another investigation into zinc dynamics within the soil-plant-animal continuum was undertaken as part of the NAIP project (38). This study involved feeding rats with zinc-biofortified wheat grain cultivated on zinc-deficient soil through a combination of soil and foliar zinc application. In addition to soil treatment, treated sewage water can also serve as a nutrient source for amending soil deficient in nutrient content. An illustrative example is the research conducted by (39). The availability of nutrient content may vary across different ecological zones. An analysis conducted in the semi-arid region (40) focused on certain micronutrients among indigenous sheep to identify the relationship between nutrient transfer from soil to the animal system. An accurate assessment of mineral status is crucial at various levels of the food chain to implement appropriate management practices for soil or plants lacking specific minerals. Such studies are essential for identifying correlations between nutrients in the soil, plant, and animal systems. Bhagat et al. (28) conducted such a study in the feed, fodder, soil, and blood serum of dairy animals in the Sindhudurg District of Maharashtra, India. A total of 386 different types of fodder and 540 blood samples from cows or buffaloes are analyzed. Another study concerning the macro and micro-mineral status of dairy cattle was conducted by (41) in a subtropical hill agroecosystem. A total of 96 soil samples, 96 fodder samples, and 120 blood samples from dairy cattle were analyzed to study the relationship within the soil-plant-animal continuum. A study was conducted by (42) in the Rohilkhand region of Uttar Pradesh to understand the interrelationship between soil and plant nutrient content, such as Zn, Cu, and Co, and the fertility status of buffaloes. Yadav and Khirwar (43) carried out a study in Haryana, India, which linked low copper levelsin buffalo milk to correspondingly low copper levels in local soils and fodder. The different studies are shown in (Table 4). These studies conclude the availability of nutrients in the soil and how they accumulate in the plants and thereby to animals and humans further certifying the dynamics of nutrients in the environment. It also gives importance to the factors associated with the nutrient availability in soil-plant-animal-continuum.

Government Initiatives

Food security and public health determine the growth of the country. In addition to satisfyinghunger and poverty, it is now necessary to have a nutrient-rich diet that can prevent nutritional disorders or malnutrition. India is a self-sufficient country, with most of its population depending on cereals as its main food source, while giving less importance to pulses, millets, and other nutrient-rich food sources. Crop diversification is a much-needed factor in increasing the quality of our food sources. It is observed that South Asian Enigma is present in India, indicating the malnutrition level in India is much worse than in certain parts of Africa (44). South Asia has significantly higher rates of undernutrition among children and adult women than Sub-Saharan Africa, even though South Asia performs better on several factors commonly associated with malnutrition, such as maternal and infant mortality, women's education, food availability, and poverty levels. This contradiction is referred to as the 'Soth Asian Enigma'. The marginalized status of women and the presence of gender inequality in the region are considered to contribute significantly to the inadequate diets of women and children in South Asia (45). It is a serious problem; a multi-disciplinary approach is urgently needed, and the government is introducing various policies and schemes to reduce malnutrition in India. Some of these schemes include the National Food Security Act, Integrated Child Development Services, Poshan Abhiyan, National Iron Plus Initiative Program, and others, which are further illustrated in (Fig. 4).

According to FAO, 'food security exists when all people, always, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (46). The two types of hunger include raw hunger, which refers to the need for calories and energy,and hidden hunger, which involves a deficiency of micronutrients, vitamins, and other essentialnutrients. This highlights the prevalence of hidden hunger in India, particularly among children andwomen, leading to issues such as anemia, stunted growth, and mental retardation (47). The two

Table 4. Case studies related to the soil-plant-animal-human

Study Area	Source of Nutrients	Objective	Findings
Tamil Nadu Agricultural University	Fodder crop enriched with Zn Nutrients	To analyze the significant relation of Zinc in the soil-plant-animal continuum	As a result of analysis of fodder, milk, dung, and blood, agronomic fortified fodder shows a significant rise in Zinc in animals.
Anaikatti village of Coimbatore, Tamil Nadu, India	Combined application of NPK and $ZnSO_4$ (Soil and Foliar Spraying) in Super Napier Variety.	To find whether Zn is transferred from soil to plants and animals, and also to find the yield variation in different treatments.	The result revealed that application of NPK + 25 kg of soil application of $ZnSO_4$ + 0.50% Foliar spray thrice at 10-day intervals significantly improved the fodder yield by 12.5%, and zinc content by 17.5%. Feeding the dairy cows with Zn-enriched fodder improved the milk Zn content by 9.6%.
Bhalwal city, Sargodha District, Punjab province of Pakistan	Treated Sewage water	To assess the bio-accumulation of macro minerals (Na, K, Ca, and Mg) in buffaloes provided hay irrigated with sewage or canal water.	Through analysis of soil, forage, and buffalo hair, the study revealed a significant positive correlation between soil, plant, and animal in the case of Ca but an imbalanced flow was observed for other nutrients.
Anantapuramu district, Andhra Pradesh, India	Cultivated fodders like Hybrid Napier, sorghum green, local grasses, or a mixture of crop residues.	To establish a soil-plant-animal continuum, measure the levels of Fe, Cu, Mn, and Zn in soil, pasture, and sheep serum in semi-arid locations with low rainfall (498-522 mm).	Zn and Mn had negative soil-plant and soil-animal interactions, however there was a positive plant-animal relationship.
Sindhudurg district of Maharashtra	Fodder crop – Irrigated and Non-irrigated type	To identify the macro and micro-mineral profile of a region and how it affects the soil-plant-animal system.	In soil Ca and Cu were found deficit. In plants, Ca, P, Mg, Zn, and in animals Ca, P, and Mg were found deficient owing to the positive correlation of these minerals in the system. P, Mg, Zn, and Fe were found adequate in soil. Similar adequacy was found in plants and animals for minerals like Cu and Fe.
Mizoram, India	Daily green fodder consumption of 8.6±1.5 kg for cattle, along with home-made concentrate feed.	To examine the relationship between soil, plants, and animals in subtropical hills.	Significant correlation values between soil and fodder for Ca, Fe, and Cu. The values for P and K were significant for fodder and cattle, with even higher significance ($P<0.01$) observed for nutrients like Ca (0.878), Mg (0.88), Cu (0.885), and Zn (0.928). However, such a correlation was not observed between soil and minerals except for Ca stating strong associations of Ca with the soil-plant-animal continuum.
Rohilkhand region, Uttar Pradesh, India	Feed and Fodder	To understand the availability and interrelationship between soil and plant nutrient content, such as Zn, Cu, and Co, and the fertility status of buffaloes.	Subsequent deficiency of nutrients below critical levels in the soil for Zn, Cu, and Co, at 30, 18, and 5 ppm, respectively. Similarly, the levels of these nutrients in crops produced in the same soil were also below normal levels. Regarding buffaloes, serum analysis showed that infertile buffaloes fed from deficient soil and plants exhibited lower concentrations of Zn, Cu, and Co content.
Jind district of Haryana, India	Feed and Fodder	To understand the availability of Cu content in the soil, the crop grown, feedstuff, and animal chain.	Copper concentration in soil was positively correlated (P<O.05) with that of berseem (+20), sorghum (+0.16), and wheat straw (+0.24). Similarly, total copper consumption was found to be positively correlated with blood copper (+0.18) and milk (+0.32) of milch buffaloes. Therefore, the level of copper in the soil was enough to meet the needs of plant growth, and hence, the feedstuffs supplied were adequate to cover the Cu requirements of animals.
Two Tribal districts of Madhya Pradesh, India	Feed, Fodder, and Food	Systematic analysis of Zn content in soil-plant-animal-human continuum	The determination coefficients (R^2) indicated a correlation of 0.36 between soil zinc content and grain zinc concentration and 0.48 between zinc concentration in human blood serum and grain zinc concentration. A positive correlation with an R^2 value of 0.61 was observed between Straw Zn concentration and animal blood serum Zinc.
NAIP Project, India	Feeding rats with Zn biofortified wheat grains which was produced in Zn deficient soil along with external soil and foliar Zn application	Systematic analysis of Zn content in the soil-plant-animal continuum.	Rats fed with wheat-based low-zinc grains exhibited lower serum zinc levels in their blood compared to those fed with high-zinc grains, suggesting a heightened efficiency in zinc absorption and bio-availability

types of hunger include raw hunger, which refers to the need for calories and energy, and hidden hunger, which involves a deficiency of micronutrients, vitamins, and other essential nutrients. It discusses the prevalence of hidden hunger in India, particularly among children and women, leading to issues such as anemia, stunted growth, and mental retardation (48). The urban HUNGaMA survey report of 2014, which was published in 2018, shows that even though India was urbanized, 22.3% of children under the age of five were stunted and 21.4% were underweight

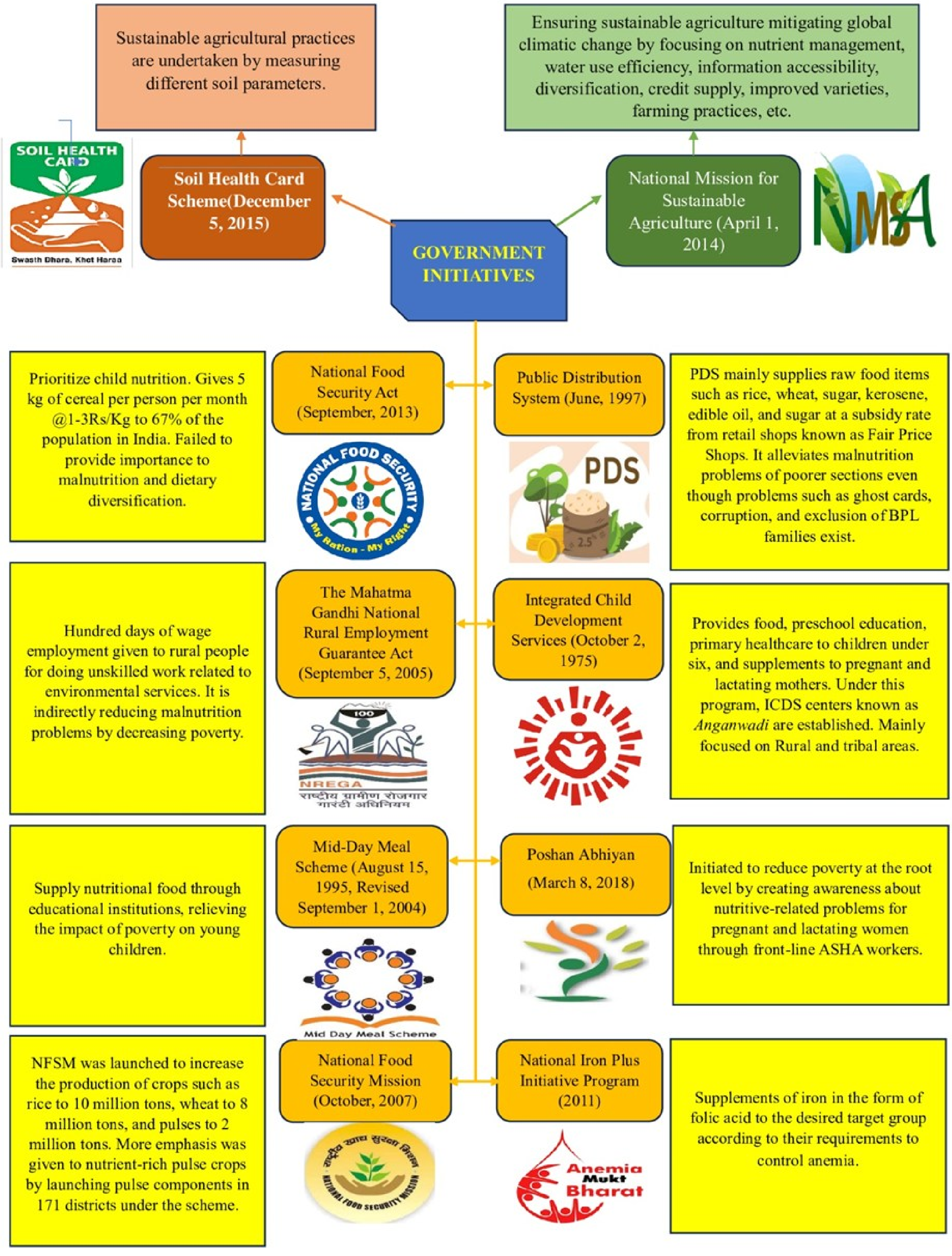

Fig. 4. Government initiatives (referred from 97-105).

in the 10 most populated cities of India (49). The problem is not limited to calorie intake but also stems from factors such as lack of micronutrients, poor hygiene, marginalization ofwomen, and inadequate breastfeeding practices. Undernutrition is a global issue, contributing to high mortality rates among children under five (50). Addressing nutrient management in diets is crucial to combat this problem.

Nutrient Management Practices

The best way to manage nutrients in animal or human diet will be through a balanced diet. Including dietary diversification in the human diet can prevent many nutritional problems. But when people are not getting enough nutrient content through food sources, because of lack of diversity or due to poverty the best way to cope will be by using supplementation or biofortification to supply nutrients, especially for developing and underdeveloped countries (51). The different management practices that can be applied at different levels of the food chain are visualized in (Fig. 5).

Nutrient management through soil

Agronomic biofortification: Micronutrient fertilizers are applied to the soil and/or plant to enrich the edible component of the field crop with micronutrients. During this technique, the appropriate nutrient is supplied topically to plants before or during their growth. Soil treatment offers enough nutrients for plants by root intake, whereas foliar application boosts thequantity of nutrients in the leaf, enabling its translocation to other plant parts. Thus, fertilizer treatment mode, soil conditions, and additions all influence mineral enrichment in each crop. Soil and foliar application of fertilizers, seed coating, and seed priming are methods that are used for mineral fortification. In addition to this, several agronomic management practices can be adopted such as the application of lime, gypsum, biochar, biosolids, elemental Sulphur, incorporation of crop residues, addition of animal manure and compost, etc. can increase the nutrient availability of plants, and thereby increase the nutrient uptake by plants (52).

Agronomic fortification can be linked to the efficiency of NPK utilization by plants. It has been observed that certain micronutrients such as zinc, have a synergistic effect with macronutrient uptake by plants, and fortification of soil with micronutrients can enhance crop yield. One of the studies conducted by (53), they observed that plant uptake of primary nutrients significantly increased with the different treatments of zinc fertilization in rice and increased crop yield and biomass.

To improve nutrient use efficiency, it is essential to understand the synergistic and antagonistic interactions between nutrients. Fertilizer formulations should avoid nutrient combinations with antagonistic effects and prioritize those with synergistic interactions (54). A notable example is the interaction between zinc and iron. When both nutrients are supplied together, the production of siderophores by plants in the Poaceae family decreases, which reduces micronutrient uptake. The reduction in zinc concentration is observed when iron is applied as fertilizer in rice and wheat cultivation, further solidifying the antagonistic interaction between these nutrients (55).

Balanced fertilization is another effective agronomic fortification that can contribute to the nutrient availability and uptake by plants. Balanced fertilization accelerates crop nutrition uptake and maintains soil nutrient balance, but also increases grain yields and farmer revenue. It was shown that N was the first nutritional limiting factor for yield, followed by K, and then P. Limited application of potassium can lead to a decreased yield, even though there is enough nitrogen present in the soil. So, it is necessary to have a balanced application of fertilizers for sustainable growth and to avoid nutrient mining of a particular nutrient (56).

VAM and Nutrient Mobilization: Research shows that certain microorganisms can mobilize the nutrients present

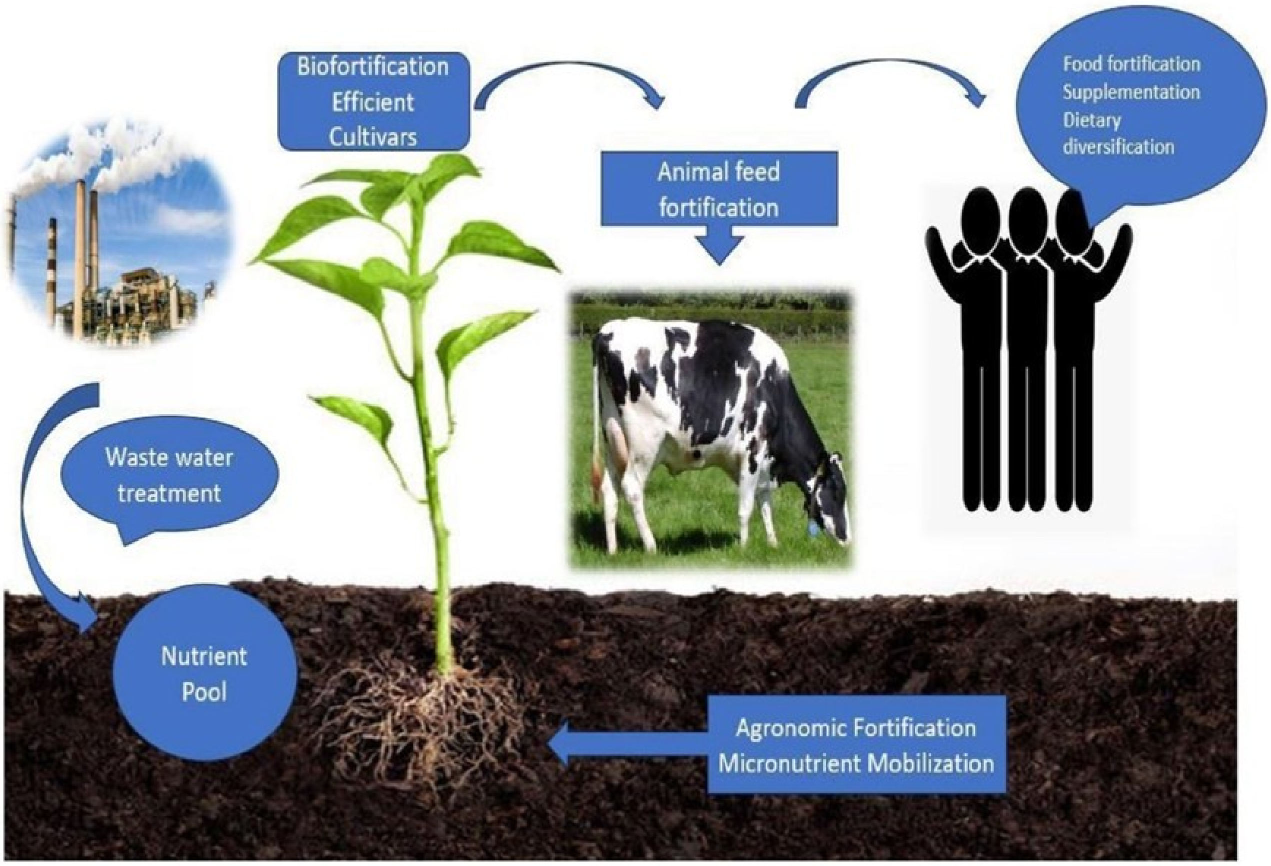

Fig. 5. Nutrient management practices in various levels of the food chain.

in the soil and make them available to the plants. An example is vesicular-arbuscular mycorrhiza. It is mainly involved in mobilizing phosphorus in the soil, making it available to plants in phosphorus-deficient conditions. In a study conducted by (57) in wheat plants, VA-mycorrhizal plants consistently had greater amounts of phosphorus, copper, and zinc in their shoot dry matter compared to non-mycorrhizal plants. This indicates their efficiency in utilizing organic phosphorus in soil for plant uptake. Arbuscular mycorrhizal (AM) symbiosis improves plant hydration and physiology under drought by expanding the absorbing surface through soil-growing hyphae, enabling water uptake even from low-potential soils (58).

Site-specific nutrient management: Precision Agriculture focuses on Site Specific Nutrient Management (SSNM), which entails regulating soil nutrients differentially across landscape zones. SSNM specialist consultants may study crop output statistics, appraise farm resources, and help farmers with their fertilizer applications. The cost of characterizing resource status and a lack of professional advisors are major barriers to implementing SSNM systems. Subsidies and compliance with environmental requirements are necessary for widespread implementation of SSNM. SSNM allows for optimal crop and pasture growth while minimizing nutrient losses to the environment by matching fertilizer rates, timing, and types (59).

Nutrient management through plants

Biofortification: It involves delivering essential micronutrients directly to staple crops. A predominantly plant-based diet often provides fewer nutrients to the animals or humans consuming them. Biofortification can directly enhance the availability of nutrients in the food source through different approaches such as genetics, breeding, and agronomic practices (60). Plant breeding can directly increase the nutrient content of a crop. More than 290 varieties of 12 biofortified crops have been released, including iron beans, zinc maize, zinc lentils, zinc cowpea, iron pearl millet, zinc rice, zinc Irish potato, iron and zinc sorghum, and calcium-rich carrot (51). Genetic Engineering and plant breeding offer the advantage of requiring investment for research and development, resulting in nutritionally enhanced crops that are fully sustainable. The different methods in biofortification include plant breeding, mutation breeding, genetic engineering, and tissue culture (61).

Efficient Cultivars: Nutrient-efficient plants produce better yields per unit of applied or absorbed nutrients compared to normal plants in similar agroecological conditions. Nutrient applications in crops have gained attention due to rising fertilizer costs and environmental concerns. Inorganic fertilizers provide most plant nutrients required for improved agricultural production. Using nutrient-efficient crop species and improved crop production systems is the most effective way to meet the food needs of growing global populations (62). Many agricultural soils lack crucial minerals for proper plant growth. Acidity, alkalinity, salinity, human exploitation, nutrient mining, farming practices, and erosion are some of the factors that result in soil degradation. Fertilizers and amendments are necessary for optimal nutrient delivery and output. Fertilizer efficiency estimates are often less than 50% for N, 10% for P, and 40% for K. Efficient plant uptake and consumption of nutrients improve fertilizer efficiency, reduce input costs, and prevent nutrient losses to ecosystems (63).

The integration of biotechnology into agriculture brought significant changes with the advent of CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology. It is a precise genome-editing tool that uses a guide RNA (gRNA) to direct the Cas9 enzyme to a specific DNA sequence, enabling targeted modifications by cutting the DNA and leveraging the cell's repair mechanisms. CRISPR facilitates plant genome editing and the development of more efficient cultivars, revolutionizing agricultural biotechnology. Its applications include enhancing crop yield, developing disease resistance, improving nutritional content, and increasing resilience to environmental stress. Compared to other genetic modification techniques, CRISPR is faster, more cost-effective, and highly efficient (64).

Nipping and Defoliation: Plants limit the accumulation of micronutrients in edible seeds through physiological and biochemical barriers. They use controlled homoeostatic systems to regulate mineral uptake and translocation, allowing for adequate nutrient accumulation in tissues. To increase micronutrient accumulation in edible seeds and grains, it is vital to consider phloem sap loading, translocation, and unloading rates in reproductive organs. Nipping (apical bud removal) and defoliation (25% leaf removal) are key procedures that alter the physiology of legume crops. Plants recover from nipping and defoliation by releasing more soluble organic acids, phytosiderophores, enzymes, and oxidants. This can result in a higher concentration of minerals in the edible portions of plants (18).

Nutrient management through food

Food fortification and supplementation: Food fortification and supplementation are perhaps the most cost-effective ways to address global mineral deficiencies. In well-developed countries, the mineral and vitamin fortification of dairy products has proven helpful. Implementing this strategy in underdeveloped countries may be difficult due to the necessity for a strong food processing and distribution infrastructure. Fortification during food processing raises product prices. Fortified items are costly for impoverished individuals living in remote rural locations. To address numerous deficiencies, it is important to create techniques for fortifying meals with several micronutrients without causing undesirable interactions. While food fortification is a long-term strategy, supplementation is a short-term strategy (61).

Dietary supplements may be defined as 'foodstuff, the purpose of which is to supplement the normal diet and which are concentrated sources of nutrients or other substances with a nutritional or physiological effect, alone or in combination, marketed in dose form.' These forms include capsules, tablets, pills, sachets of powder, ampoules of liquids, drop-dispensing bottles, and similar forms of liquids and powders designed to be taken in measured small-unit quantities (65).

In the study conducted by (66) on dietary intake of food taken and supplements, it is observed that nutrient intake from food plus supplements was significantly higher ($p < 0.01$) than from food alone for all nutrients except phosphorus and vitamin K. Furthermore, the use of dietary supplements significantly enhanced nutritional intakes while decreasing the prevalence of nutrient insufficiency across all age groups. Nutrient deficiencies have been associated with adverse health consequences, such as stroke, cardiovascular disease, poor bone health, impaired cognitive function, cancer, eye diseases, and others.

Dietary Diversification: To prevent malnutrition, one of the possible methods other than supplementation is dietary diversification. As a result, it is critical to diversify the plant -based diet. Consumers benefit from grouping foods according to nutritional relationship because it allows them to quickly identify nutritionally unique plant foods, saves cognitive work and time for each meal decision, and guides a balanced diet. Furthermore, it may allow farmers to detect or switch between plants with similar or different nutrients based on seed availability, budget, and growth conditions. Food makers can even profit from this classification tool when moving between plant sources that have comparable nutrients during reformulation (67). In the Indian context, it is necessary to have diversity in the diet since the major food source consists of cereals, which have less micronutrient content. It is also necessary to include millet as a major food source. Millet is high in fiber, protein, and minerals. Despite their nutritional benefits, several countries have reduced consumption and cultivation of millets due to issues such as restricted availability of improved seed types, inadequate post-harvest infrastructure, insecure market links, and insufficient official support for millet production and sales. Including millets in integrated farming systems diversifies agricultural processes and improves ecosystem services, including soil health and biodiversity. This can alleviate hidden hunger and ensure global security (68).

Animal Feed Biofortification: Plant breeding has historically prioritized production over the dietary significance of cereal leftovers like bran and straw, which are not consumed by humans. Bran and straw are crucial feed for ruminant cattle in regions where millet and sorghum are staple grains, alongside rice and wheat. Crop management approaches and plant breeding programs increased production and hay value for livestock nutrition in sorghum and pearl millet. Genetic markers (QTL mapping and MAS) have been utilized to enhance breeding efficiency, supplementing previous research. A unique approach to increasing cereal nutrition availability has seen significant progress. Transgenic animals, such as the Enviropig, produce phytase in their salivary glands and secrete the active enzyme into saliva. These pigs have enhanced phosphorus uptake. Transgenic pigs may have better iron uptake in the intestine due to reduced antinutritional phytate levels (69).

Supplementation in Animals: When animals are not getting enough nutrients from feed and fodder, additional nutrients can be supplemented. One example is the TANUVAS mineral mixture. It is a mixture given to animals particularly cattle, to improve nutrient deficiency and improve milk yield (500-1000 ml/day/cow). The quantity may vary according to the body mass of cattle. It contains both macro and microminerals such as Ca, P, Mg, Na, Cl, Fe, Mn, Cu, Co, I, and Se (70).

Nutrient management through government policies and missions

The government of India has put forward many schemes, missions, and policies to manage the nutrients effectively in the soil-plant-animal-human continuum and to supply nutrients at various levels. In India, potash consumption is primarily determined by three factors: government-set maximum retail pricing, import availability, and the presence of potash transporting complexes.Urea supplies have been good, but other fertilizer products have not been as reliable. In the 1970s, a lack of potash and transportation in northern India contributed to an unbalanced NPK ratio. Farmers tended to apply more nitrogen and phosphorus fertilizers, which showed immediate effects on plant growth, whereas potassium fertilizers only showed quality effects at harvest time. In 1993, India implemented a concession system for phosphatic and potassium fertilizers, which subsidized the sale of potash. Beginning April 1, 2010, the government implemented the Nutrient-Based Subsidy Scheme (NBS). This applies to DAP, MOP, MAP, TSP, Indigenous ammonium sulfate, and 12 grades of complex fertilizers. The policy sets subsidy rates per kg of nutrient for N, P, K, and S at Rs 23.227, Rs 26.276, Rs 24.487, and Rs 1.784, respectively. The Nutrient-Based Subsidy Scheme is mainly employed to ensure a balanced supply of nutrients (71).

Nutrient management through technological advancement

In addition to soil, water, and forest resources, information regarding crops, cropping patterns, and nutrient status is required to establish spatial data infrastructure. Remote sensing, GIS, and GPS technologies are helpful tools for obtaining this information. They integrated spatial data on various resource themes to create alternative development plans that highlight site-specific industrial activities (72). Sustainable agricultural production systems require both geographical and temporal variability. Best Management Practices require extensive soil samples to analyze nutrient changes across the field. GIS allows for data categorization, mapping of nutrient fluctuation, and many query and analysis options. The data pertinent to the remote sensing provides additional spatial information. Using this information successfully we can manage pest attacks, weather effects, nutrient stress, and more (73). Precision agriculture is yet another approach that uses modern technologies to enhance crop production, marking a significant shift from traditional practices toward data-driven approaches. The integration of artificial intelligence (AI) has transformed farming by improving efficiency, productivity, and sustainability through real-time data analysis. Key technologies like the Internet of Things (IoT), big data analytics, and deep learning enable better farming practices through data collection, analysis, and informed decision-making. Adaptive AI tools, including sensor technology, machine learning, and computer vision, play a crucial role in monitoring plant health, scheduling irrigation and fertilization, and detecting diseases. This will ultimately boost crop yields and promote sustainable farming practices (74).

Conclusion

Effective nutrient management is critical for nutrient security, promoting sustainable agriculture, and maintaining a well-balanced ecosystem. The nutrient nexus highlights the interconnection between soil health, plant growth, animal nutrition, and human well-being. Understanding these relationships allows us to develop strategies that optimize nutrient distribution, and minimize nutrient loss. These strategies also build up the resilience of food production systems. Addressing nutrient imbalances, such as deficiencies or toxicities, requires collaboration across various fields and stakeholders. Government policies, administrative changes, and technological advancements are essential for enabling efficient nutrient management. Strategies such as crop biofortification, dietary diversification, food fortification, and supplementation can address nutrient deficiencies and ensure access to a nutrient-rich diet for everyone. Integrating traditional knowledge and modern science allows for a broader approach to nutrient management that considers local assets, cultural practices, and the surrounding environment. Research, education, and awareness programs are critical for promoting efficient management of nutrients among farmers, policymakers, and the public. Adopting a systems-based approach and encouraging multi-sector collaboration can help create a sustainable and inclusive future. This includes balancing nutrient cycles and ensuring the well-being of soil, plants, animals, and humans. Ultimately, effective nutrient management is not only crucial for food security but also for preserving the delicate harmony of our planet's ecosystems for subsequent generations.

Future Aspects

In developing countries, particularly in India, the main challenge in implementing such practices is the limitation of land resources. To address this issue, efficient management of available resources through modern technologies, such as artificial intelligence and remote sensing, can enhance balanced nutrient cycling. Food fortification and supplementation are often opposed in developing countries due to their high costs. To address this, effective organizations can be established to monitor fortified foods and ensure their distribution to the public. The feeds consumed by animals should also be given equal importance, as nutrients are passed from animals to humans, and for the well-being of animals themselves. Additionally, programs that emphasize the connection between the soil-plant-animal-human continuum can improve nutrient nexus across the systems.

Acknowledgment

Authors thanks to the Department of Soil Science and Agricultural Chemistry and Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Author’s contributions

Conceptualization was carried out by M. Soorya and S. Suganya. Resources were provided by M. Elayarajan, P. Chitra, and V. Davamani. Data collection and visualization were performed by all authors. The original draft was written by M. Soorya and S. Suganya. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI in scientific writing: During the preparation of this work, we used Grammarly for manuscript correction and BioRender for creating illustrations. After utilizing these tools/services, we carefully reviewed and edited the content as necessary and took full responsibility for the final content of the publication.

References

1. Samaddar S, Karp DS, Schmidt R, Devarajan N, McGarvey JA, Pires AF, Scow K. Role of soil in the regulation of human and plant pathogens: soils' contributions to people. Philosophical Transactions of the Royal Society B. 2021;376 (1834):20200179.https://doi.org/10.1098/rstb.2020.0179
2. Rekik F, van Es HM. The soil health–human health nexus: mineral thresholds, interlinkages and rice systems in Jharkhand, India. Adv Agron. 2022;172:67-127. https://doi.org/10.1016/bs.agron.2021.10.001
3. Lal R. Regenerative agriculture for food and climate. J Soil Water Conserv. 2020;75(5):123A-24A. https://doi.org/10.2489/jswc.2020.0620A
4. Telo da Gama J. The role of soils in sustainability, climate change and ecosystem services: Challenges and opportunities. Ecologies. 2023;4(3):552-67. https://doi.org/10.3390/ecologies4030036
5. Doran JW, Parkin TB. Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA, editors. Defining soil quality for a sustainable environment. Soil Science Society of America. 1994;35:1-21. https://doi.org/10.2136/sssaspecpub35.c1
6. Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, De Goede R, et al. Soil quality–a critical review. Soil Biol Biochem. 2018;120:105-25. https://doi.org/10.1016/j.soilbio.2018.01.030

7. Wani FS, Ahmad L, Ali T, Mushtaq A. Role of microorganisms in nutrient mobilization and soil health—a review. J Pure Appl Microbiol. 2015;9(2):1401-10.

8. Sanyal SK, Majumdar K, Singh VK. Nutrient management in Indian agriculture with special reference to nutrient mining—A relook. J Ind Soc Soil Sci. 2014;62(4):307-25.

9. van Bruggen AH, Goss EM, Havelaar A, van Diepeningen AD, Finckh MR, Morris Jr JG. One health-cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health. Sci Total Environ. 2019;664:927-37. https://doi.org/10.1016/j.scitotenv.2019.02.091

10. Chen Y, Michalak M, Agellon LB. Focus: nutrition and food science: importance of nutrients and nutrient metabolism on human health. The Yale J Biol Med. 2018;91(2):95.

11. Yelverton CA, Rafferty AA, Moore RL, Byrne DF, Mehegan J, Cotter PD, et al. Diet and mental health in pregnancy: nutrients of importance based on large observational cohort data. Nutrition. 2022;96:111582. https://doi.org/10.1016/j.nut.2021.111582

12. Cobre AF, Surek M, Vilhena RO, Böger B, Fachi MM, Momade DR, et al. Influence of foods and nutrients on COVID-19 recovery: a multivariate analysis of data from 170 countries using a generalized linear model. Clin Nutri. 2022;41(12):3077-84. https://doi.org/10.1016/j.clnu.2021.03.018

13. White PJ, Broadley MR, Gregory PJ. Managing the nutrition of plants and people. Appl Environ Soil Sci. 2012;2012(1):104826.https://doi.org/10.1155/2012/104826

14. Javed A, Ali E, Afzal KB, Osman A, Riaz S. Soil fertility: Factors affecting soil fertility and biodiversity responsible for soil fertility. Int J Plant, Animal Environ Sci. 2022;12(1):21-33. https://doi.org/10.26502/ijpaes.202129

15. Kim K, Bevis L. Soil fertility and poverty in developing countries. Choices. 2019;34(2):1-8. https://www.jstor.org/stable/26785776

16. Eliazer Nelson AR, Ravichandran K, Antony U. The impact of the green revolution on indigenous crops of India. J Ethnic Foods. 2019;6(1):1-0. https://doi.org/10.1186/s42779-019-0011-9

17. Hodges SC. Soil fertility basics. Soil science extension. North Carolina State University. 2010;p. 1-75.

18. Shukla AK, Behera SK, Pakhre A, Chaudhari SK. Micronutrients in soils, plants, animals and humans. Ind J Fertil. 2018;14(3):30-54.

19. Brown PH, Zhao FJ, Dobermann A. What is a plant nutrient? Changing definitions to advance science and innovation in plant nutrition. Plant Soil. 2022;476(1):11-23. https://doi.org/10.1007/s11104-021-05171-w

20. Toor MD, Adnan M, Rehman FU, Tahir R, Saeed MS, Khan AU, Pareek V. Nutrients and their importance in agriculture crop production- A review. Ind J Pure App Biosci. 2021;9(1):1-6. http://dx.doi.org/10.18782/2582-2845.8527

21. Pandey N. Role of plant nutrients in plant growth and physiology. In: Hasanuzzaman M, Fujita M, Oku H, Nahar K, Hawrylak-Nowak B, editors. . Plant nutr abiotic stress tolerance. Singapore: Springer; 2018. p. 51-93. https://doi.org/10.1007/978-981-10-9044-8-2

22. Huber DM, Graham RD. The role of nutrition in crop resistance and tolerance to diseases. In: Rengel Z, editor. Mineral nutrition of crops fundamental mechanisms and implications. New York: Food Product Press; 1999. p. 205-26.

23. Sharma MC, Joshi C, Das G, Hussain K. Mineral nutrition and reproductive performance of the dairy animals: a review. Ind J Animal Sci. 20071;77(7):599-608.

24. Underwood EJ, Suttle NF. The mineral nutrition of livestock, 3rd ed. CABI Digital Library; 2000 https://doi.org/10.1079/9780851991283.0000

25. Cherian G. A guide to the principles of animal nutrition. Oregon State University; 2020.

26. Pervaiz ZH, Iqbal J, Zhang Q, Chen D, Wei H, Saleem M. Continuous cropping alters multiple biotic and abiotic indicators of soil health. Soil Sys. 2020;4(4):59. https://doi.org/10.3390/soilsystems4040059

27. Huth PJ, DiRienzo DB, Miller GD. Major scientific advances with dairy foods in nutrition and health. J Dairy Sci. 2006;89(4):1207-21. https://doi.org/10.3168/jds.S0022-0302(06)72190-7

28. Bhagat DJ, Burte RG, Kumar S, Pawar JK, Dhopavkar RV, Gurav SS. Assessment of mineral status in feed and fodder, soil and blood serum of dairy animals in Sindhudurg district of Maharashtra, India. Adv Agri Res Technol J. 2017;1(1):52-56.

29. Miller DD. Minerals. In: Fennema's food chemistry. 5th ed. CRC Press; 2017. p. 627-79

30. Gharibzahedi SM, Jafari SM. The importance of minerals in human nutrition: bioavailability, food fortification, processing effects and nanoencapsulation. Trends Food Sci Technol. 2017;62:119-32. https://doi.org/10.1016/j.tifs.2017.02.017

31. Majumdar K, Sanyal SK, Dutta SK, Satyanarayana T, Singh VK. Nutrient mining: addressing the challenges to soil resources and food security. Biofortification of Food Crops. 2016;177-98.https://doi.org/10.1007/978-81-322-2716-8_14

32. Brown LR. World population growth, soil erosion and food security. Science. 1981;214(4524):995-1002. https://doi.org/10.1126/science.7302578

33. Mayland HF. Assessing nutrient cycling in the soil/plant animal system of semi-arid pasture lands. In: Nuclear techniques in improving pasture management. Atomic Energy Agency: Vienna; 1983. p. 109-17. https://eprints.nwisrl.ars.usda.gov/id/eprint/767

34. Whitehead DC. Nutrient elements in grassland: soil-plant-animal relationships. CABI; 2000. https://doi.org/10.1079/9780851994376.00

35. Johnston AM, Bruulsema TW. 4R nutrient stewardship for improved nutrient use efficiency. Proc Engin. 2014;83:365-70. https://doi.org/10.1016/j.proeng.2014.09.029

36. Annual Report. All India coordinated research project on micro- and secondary nutrients and pollutant elements in soils and plants (AICRP-MSPE), Tamil Nadu Agricultural University, Coimbatore. 2013-2014.

37. Annual Report. All India coordinated research project on micro- and secondary nutrients and pollutant elements in soils and plants (AICRP-MSPE), Tamil Nadu Agricultural University, Coimbatore, 2022-2023.

38. Shukla AK, Tiwari PK, Pakhare A, Prakash C. Zinc and iron in soil, plant, animal and human health. Indian J Fertil. 2016;12(11):133-49.

39. Khan ZI, Ahmad K, Ashraf I, Gondal S, Sher M, Hayat Z, et al. Bioconcentration of some macro minerals in soil, forage and buffalo hair continuum: a case study on pasture irrigated with sewage water. Saudi J Biol Sci. 2015;22(3):249-55. https://doi.org/10.1016/j.sjbs.2014.11.016

40. Raju NV, Parashar A, Pankaj PK. Soil-plant-animal continuum concerning the certain micro-mineral status of indigenous sheep in hot semi-arid regions. Ind J Animal Res. 2022;56(6):688-94. http://dx.doi.org/10.18805/IJAR.B-4854

41. Kumaresan A, Bujarbaruah KM, Pathak KA, Brajendra, Ramesh T. Soil–plant–animal continuum in relation to macro and micro mineral status of dairy cattle in subtropical hill agro ecosystem. Trop Aanimal health Prod. 2010;42:569-77. https://doi.org/10.1007/s11250-009-9459-8

42. Singh B, Rawal CV, Swarup D. Soil-plant-animal relationship of Zn, Cu and Co in buffaloes of Rohilkhand region. Ind J Animal Sci. 2007;77(1):83-85.

43. Yadav S, Khirwar SS. Soil-plant-animal relationship of copper in milch buffaloes of Jind district in Haryana. Indian J Animal Sc. 1999;69(9).718-21.

44. Dev SM, Sharma AN. Food security in India: Performance, challenges and policies. Oxfam India; 2010.

45. Nubé M. The Asian enigma: predisposition for low adult body mass index among people from South Asian descent. Staff Working Paper WP-07-01. Amsterdam: Centre for World Food Studies; 2007.

46. Vijayan B, Nain MS, Singh R, Kumbhare NV. Knowledge test for extension personnel on National food security mission. Ind J Ext Edu. 2022;58(2):191-94. http://doi.org/10.48165/IJEE.2022.58246

47. Gopaldas T. Hidden hunger: The problem and possible interventions. Econ Pol Week. 2006;26:3671-74. https://www.jstor.org/stable/4418615

48. Mehta AK, Bhide S, Kumar A, Shah A. Poverty, chronic poverty and poverty dynamics; policy imperatives. Eds. Singapore: Springer; 2018.https://doi.org/10.1007/978-981-13-0677-8

49. Gogoi NN. Ensuring food security and human security: an assessment of the security challenges in India. PalArch's J Archaeol Egypt/Egyptol. 2020;17(9):8697-703.

50. Goulet O, Lebenthal E, Branski D, Martin A, Antoine JM, Jones PJ. Nutritional solutions to major health problems of preschool children: how to optimise growth and development. J Pediatr Gastroenterol Nutr. 2006;43:S1-3.https://doi.org/10.1097/01.mpg.0000255843.54164.af

51. Bouis HE, Saltzman A, Birol E. Improving nutrition through biofortification. In: Fan S, Yosef S, Pandya-Lorch R, editors. Agriculture for improved nutrition: seizing the momentum. Wallingford UK: CAB International; 2019. p. 47-57. https://doi.org/10.1079/9781786399311.0047

52. Dhaliwal SS, Sharma V, Shukla AK, Verma V, Kaur M, Shivay YS, et al. Biofortification—a frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security. Molecules. 2022;27(4):1340. https://doi.org/10.3390/molecules27041340

53. Regar KL, Kumar V, Chandola JC, Patel SS, Singh AK, Kundu MS, Singh SK. Zinc fertilization: effects on nutrients availability and productivity of rice (*Oryza sativa* L.). Int J Plant Soil Sci. 2022;34(12):41-47. https://doi.org/10.9734/ijpss/2022/v34i1230958

54. Rietra RP, Heinen M, Dimkpa CO, Bindraban PS. Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. Comm Soil Sci Plant Anal. 2017;48(16):1895-920. https://doi.org/10.1080/00103624.2017.1407429

55. Prasad R, Shivay YS, Kumar D. Interactions of zinc with other nutrients in soils and plants- A Review. Ind J Fertil. 2016;12(5):16-26.

56. Xing Y, Wang R, Sun W, An J, Wang C, Bao H, et al. Effect of balanced fertilization on rice nutrient uptake, yield and profit. Better Crops. 2009;93(1):5.

57. Tarafdar JC, Marschner H. Efficiency of VAM hyphae in utilisation of organic phosphorus by wheat plants. Soil Sci Plant Nutr. 1994;40(4):593-600. https://doi.org/10.1080/00380768.1994.10414298

58. Ruiz-Lozano JM, Porcel R, Bárzana G, Azcón R, Aroca R. Contribution of arbuscular mycorrhizal symbiosis to plant drought tolerance: state of the art. In: Aroca R, editor. Plant responses to drought stress: from morphological to molecular features. Berlin: Springer; 2012. p. 335-62. https://doi.org/10.1007/978-3-642-32653-0_13

59. Betteridge K, Schnug E, Haneklaus S. Will site specific nutrient management live up to expectation. Agri Forest Res. 2008;4(58):283-94.

60. Hirschi KD. Nutrient biofortification of food crops. Ann Rev Nutr. 2009;29(1):401-21. https://doi.org/10.1146/annurev-nutr-080508-141143

61. Khush GS, Lee S, Cho JI, Jeon JS. Biofortification of crops for reducing malnutrition. Plant Biotechnol Rep. 2012;6:195-202. https://doi.org/10.1007/s11816-012-0216-5

62. Fageria NK, Baligar VC, Li YC. The role of nutrient efficient plants in improving crop yields in the twenty first century. J Plant Nutr. 2008;31(6):1121-57. https://doi.org/10.1080/01904160802116068

63. Baligar VC, Fageria NK, He ZL. Nutrient use efficiency in plants. Comm Soil Sci Plant Anal. 2001;32(7-8):921-50. https://doi.org/10.1081/CSS-100104098

64. Sampath V, Rangarajan N, CH S, Deori M, Veeraragavan M, Ghodake BD, Kaushal K. Advancing crop improvement through CRISPR technology in precision agriculture trends -a review. Int J Environ Clim Chng. 2023;13(11):4683-94. https://doi.org/10.9734/ijecc/2023/v13i113647

65. Lentjes MA. The balance between food and dietary supplements in the general population. Proc Nutr Soc. 2019;78(1):97-109. https://doi.org/10.1017/S0029665118002525

66. Blumberg JB, Frei B, Fulgoni Iii VL, Weaver CM, Zeisel SH. Contribution of dietary supplements to nutritional adequacy in various adult age groups. Nutrients. 2017;9(12):1325. https://doi.org/10.3390/nu9121325

67. Li Y, Bahadur R, Ahuja J, Pehrsson P, Harnly J. Macro-and micronutrients in raw plant foods: The similarities of foods and implication for dietary diversification. J Food Comp Anal. 2021;102:103993. https://doi.org/10.1016/j.jfca.2021.103993

68. Tiwari H, Singh PK, Naresh RK, Islam A, Kumar S, Singh KV, et al. Millets based integrated farming system for food and nutritional security, constraints and agro-diversification strategies to fight global hidden hunger: A review. Int J Plant Soil Sci. 2023;35(19):630-43. https://doi.org/10.9734/ijpss/2023/v35i193593

69. Singh U, Praharaj CS, Chaturvedi SK, Bohra A. Biofortification: Introduction, approaches, limitations and challenges. In: Singh U, Praharaj C, Singh S, Singh N, editors. Biofortification of food crops. New Delhi: Springer; 2016. p. 3-18. https://doi.org/10.1007/978-81-322-2716-8_1

70. TNAU Agritech Portal 2014, TANUVAS - Technologies website, accessed on June 2023. https://agritech.tnau.ac.in/animal_husbandry/animhus_tanuvas_tech_feed.html

71. Kinekar BK. Potassium fertilizer situation in India: current use and perspectives. Karnataka J Agri Sci. 2011;24(1):1-6.

72. Sharma PK. Emerging technologies of remote sensing and GIS for the development of spatial data infrastructure. The 2nd Dr. R. R. Agarwal Memorial Lecture. CSK Himachal Pradesh Krishi Vishavvidalaya, Palampur. 2004.

73. Sarkar D, Meena VS, Haldar A, Rakshit A. Site-specific nutrient management (SSNM): a unique approach towards maintaining soil health. In: Rakshit A, Abhilash P, Singh H, Ghosh S, editors. Adaptive soil management: from theory to practices. Singapore: Springer; 2017. p. 69-88. https://doi.org/10.1007/978-981-10-3638-5_3

74. Akintuyi OB. Adaptive AI in precision agriculture: a review: investigating the use of self-learning algorithms in optimizing farm operations based on real-time data. Res J Multidiscipl Stud. 2024;7(02):016-30. https://oarjpublication.com/journals/oarjms/

75. Uchida R. Essential nutrients for plant growth: nutrient functions and deficiency symptoms. In: Silva JA, Uchida R, editors. Plant nutrient management in Hawaii's soils, approaches for tropical and subtropical agriculture. Manoa: University of Hawaii; 2000. p.31-55.

76. McCauley A, Jones C, Jacobsen J. Plant nutrient functions and deficiency and toxicity symptoms. Nutr Manag Mod. 2009;9:1-6.

77. Fageria VD. Nutrient interactions in crop plants. J Plant Nutri. 200131;24(8):1269-90. https://doi.org/10.1081/PLN-100106981

78. Farber JL. The role of calcium ions in toxic cell injury. Environ Health Perspect. 1990;84:107-11. https://doi.org/10.1289/ehp.9084107

79. Verbruggen N, Hermans C. Physiological and molecular responses to magnesium nutritional imbalance in plants. Plant Soil. 2013;368:87-99. https://doi.org/10.1007/s11104-013-1589-0

80. Linzon SN, Temple PJ, Pearson RG. Sulfur concentrations in plant foliage and related effects. J Air Poll Ctrl Asso. 1979;29 (5):520-25. https://doi.org/10.1080/00022470.1979.10470822

81. Rout GR, Das P. Effect of metal toxicity on plant growth and metabolism: I. Zinc. In: Lichtfouse E, Navarrete M, Debaeke P, Véronique S, Alberola C. editors. Sustainable agriculture. Dordrecht: Springer; 2009. p. 873-84. https://doi.org/10.1007/978-90-481-2666-8_53

82. Foy CD, Chaney RT, White MC. The physiology of metal toxicity in plants. Ann Rev Plant Physiol. 1978;29(1):511-66.https://doi.org/10.1146/annurev.pp.29.060178.002455

83. Brdar-Jokanović M. Boron toxicity and deficiency in agricultural plants. Int J M Sci. 2020;21(4):1424. https://doi.org/10.3390/ijms21041424

84. Yruela I. Copper in plants. Braz J Plant Physiol. 2005;17:145-56. https://doi.org/10.1080/00103624.2020.1836200

85. Kumchai J, Huang JZ, Lee CY, Chen FC, Chin SW. Proline partially overcomes excess molybdenum toxicity in cabbage seedlings grown *in vitro*. Genet Mol Res. 2013;12:5589-601.https://doi.org/10.4238/2013.November.18.8

86. Geilfus CM. Review on the significance of chlorine for crop yield and quality. Plant Sci. 2018;270:114-22. https://doi.org/10.1016/j.plantsci.2018.02.014

87. Razzaque MS. Phosphate toxicity: new insights into an old problem. Clin Sci. 2011;120(3):91-97. https://doi.org/10.1042/CS20100377

88. Araya M, Olivares M, Pizarro F. Copper in human health. Int J Environ Health. 2007;1(4):608-20. https://doi.org/10.1504/IJENVH.2007.018578

89. Awuchi CG, Igwe VS, Amagwula IO. Nutritional diseases and nutrient toxicities: A systematic review of the diets and nutrition for prevention and treatment. Int J Adv Acad Res. 2020;6(1):1-46. https://doi.org/10.46654/ij.24889849.e61112

90. Brown RB. Sodium toxicity in the nutritional epidemiology and nutritional immunology of COVID-19. Medicina. 202122;57 (8):739. https://doi.org/10.3390/medicina57080739

91. Gupta UC, Gupta SC. Sources and deficiency diseases of mineral nutrients in human health and nutrition: a review. Pedosphere. 2014;24(1):13-38. https://doi.org/10.1016/S1002-0160(13)60077-6

92. Prasad R, Shivay YS. Sulphur in soil, plant and human nutrition. Proc Nat Acad Scie, India Sec B: Biol Sci. 2018;88:429-34. https://doi.org/10.1007/s40011-016-0769-0

93. Shankar AH. Mineral deficiencies. In: Hunter's Tropical Medicine and Emerging Infectious Diseases. Elsevier; 2020. p. 1048-54. https://doi.org/10.1016/B978-0-323-55512-8.00145-9

94. Shekhawat K, Chatterjee S, Joshi B. Chromium toxicity and its health hazards. Int J Adv Res. 2015;3(7):167-72.

95. Udensi UK, Tchounwou PB. Potassium homeostasis, oxidative stress and human disease. Int J Clin Exp Physiol. 2017;4(3):111. https://doi.org/10.4103/ijcep.ijcep_43_17

96. TNAU Agritech Portal 2023, Crop wise deficiency symptoms, accessed on August 2024. http://www.agritech.tnau.ac.in/horticulture/horti_deficienciesanddisorders.html

97. Bhaskar S, Ravisankar N, Dey P, Raghavendra KJ, Panwar AS. Impact and refinement of soil health card-based nutrient management in major cropping systems in India. Indian Journal of Fertilisers. 2021 Nov;17(11):1108-22.

98. Morya GP, Mehta J. Climate change management in rural livelihood of India. Emrg Trnd Clim Chng. 2023;2(1):49-56.

99. Tarozzi A. The Indian public distribution system as provider of food security: Evidence from child nutrition in Andhra Pradesh. Eur Econ Rev. 2005;49(5):1305-30. https://doi.org/10.1016/j.euroecorev.2003.08.015

100. Srinivasarao CH. Programmes and policies for improving fertilizer use efficiency in agriculture. Ind J Fertil. 2021;17(3):226-54.

101. Lokshin M, Das Gupta M, Gragnolati M, Ivaschenko O. Improving child nutrition? The integrated child development services in India. Dev Chng. 2005;36(4):613-40. https://doi.org/10.1111/j.0012-155X.2005.00427.x

102. Deodhar SY, Mahandiratta S, Ramani KV, Mavalankar D, Ghosh S, Braganza V. An evaluation of mid-day meal scheme. J Indian School Pol Eco. 2010;22(1-4):33-49.

103. Paul VK, Singh A, Palit S. POSHAN abhiyaan: making nutrition a jan andolan. Proc Ind Natl Sci Aca. 2018;84(4):835-41. 10.16943/ptinsa/2018/49452

104. Thomas L, Sundaramoorthy C, Jha GK. The impact of national food security mission on pulse production scenario in India: an empirical analysis. Int J Agricult Stat Sci. 2013;9(1):213-23.

105. Kapil U, Kapil R, Gupta A. National iron plus initiative: current status and future strategy. Ind J Med Res. 2019;150(3):239-47. 10.4103/ijmr.IJMR_1782_18. https://doi.org/10.4103/ijmr.IJMR_1782_18