



REVIEW ARTICLE

Nutrient nexus: Linking soil, plants, animals and humans

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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).

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

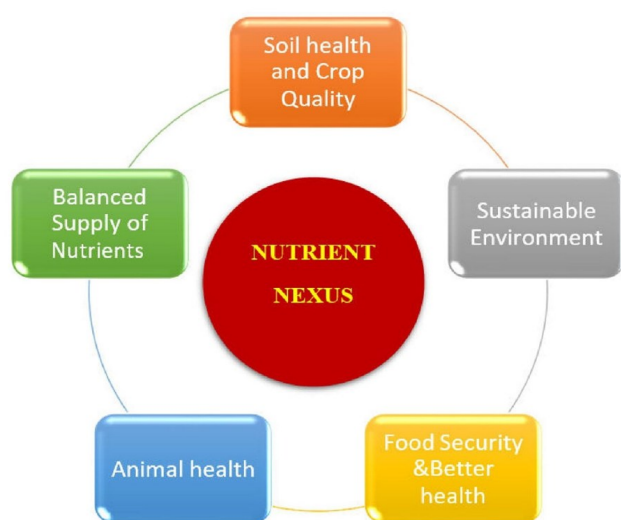


Fig. 1. Nutrient nexus: linking soil, plants, animals, and humans.

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 (>1 ppm), which are again classified as primary nutrients (C (carbon), H (hydrogen), O (oxygen), N (nitrogen), P (phosphorus) and K (potassium)) and secondary nutrients (Ca (calcium), Mg (magnesium), S (sulfur), Na (sodium) and Si (silicon)). 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 (<1 ppm), which include Fe (iron), Mn (manganese), Zn (zinc), Cu (copper), B (boron), Mo (molybdenum), Cl (chlorine), Co (cobalt) and Va (vanadium). 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 and pH (17). The micronutrients are needed in smaller amounts, and their deficiency may lead to adverse effects in 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 hidden hunger 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 ‘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 (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 P and 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 K, Na, Ca, Mg, Mn, and 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 Fe, Cu, Zn and 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 (*Pseudocercospora 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 (23, 24-34).

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 (35).

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 (36). Macronutrients such as Ca, P, Mg, S, Na, K and Cl and micronutrients such as Mn, Zn, Fe, Cu, Se, I, Co and 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 %). Ca plays a role in blood coagulation, enzyme activation, muscle contraction, ion channel regulation, nerve impulse transmission, and membrane permeability. P is a key component of ATP (adenosine triphosphate), DNA (deoxyribonucleic acid), RNA (ribonucleic acid), and phospholipids, supporting nutrient transport and cellular fluidity. Mg activates enzymes and is involved in carbohydrate and protein metabolism. S is 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. Na, K, and Cl act as electrolytes, regulating pH, osmotic pressure, and cell signaling. Na 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. Mn is necessary

Table 1. Deficiency symptoms (23) and toxicity symptoms (24-34) in plants

Nutrients	Deficiency in plants	Toxicity in plants	References
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.	(24)
Phosphorus	Slow, stunted growth, dark to blue-green leaves, purpling, delayed maturity, and poor seed and fruit development.	Reduction of Fe, Zn, Mn uptake.	(24)
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 B availability, decreased translocation from roots to shoots.	(25)
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.	(26)
Magnesium	Older leaves show interveinal chlorosis, 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.	(27)
Sulfur	Chlorosis on young leaves, inhibited growth rate, and delayed maturity. Rigid, slender, and woody stems resembling nitrogen shortage symptoms.	Acute injury as interveinal lesions on broad leaves of plants, chlorosis.	(28)
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 interveinal chlorotic leaf patches in legumes.	Curling and rolling of young leaves, stunting of roots, chlorosis, death of leaf tips, inhibit root growth.	(29)
Iron	Interveinal chlorosis in immature leaves resulting the appearance of a white color 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.	(30)
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 calyx in 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, number of spikes per plant, and yield.	(31)
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.	(32)
Manganese	Chlorosis with yellow patches in dicots, greenish-grey flecks later turning to golden to 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.	(30)
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 of seedlings.	(33)
Chlorine	Plant wilting and chlorosis in young leaves.	Chlorotic leaves, necrotic leaf edges, leaf abscission.	(34)

for carbohydrate metabolism, bone formation, and acts as a cofactor in lipid metabolism. Zn is involved in over 100 enzyme functions, insulin synthesis, immunity, and reproductive health. Fe is essential for haemoglobin production and functions as a cofactor for enzymes like cytochromes, catalases, and peroxidases. Cu supports blood formation, enzymatic processes, and the conversion of tyrosine to melanin pigment. Se is a component of glutathione peroxidase and deiodinase enzymes. Co, found in tissues like the liver and kidneys, is part of vitamin B12 and aids in volatile fatty acid metabolism. I is a constituent of thyroid hormones, regulating cellular oxidation and basal metabolic rate (BMR). Mo acts as a cofactor for xanthine oxidase and nitrogenase enzymes. Cr plays a role in glucose metabolism, enhances immunity, and reduces respiratory problems in cattle. Cr is added to

swine feed to enhance metabolic efficiency, promoting lean muscle growth by redirecting energy from fat storage, thereby reducing carcass fat (37). Even though the elements are essential to animals for their normal growth, the imbalanced intake of dietary nutrients can lead to deficiency or toxicity and cause several problems which are listed in Table 2 (37, 38).

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 physiochemical changes in the soil, including shifts in pH, soil structure, and nutrient balance, ultimately degrading the soil and depleting essential nutrients (39). 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 K, P, Mg, Zn, Mn, Cu, among others (40). Studies have demonstrated that animals fed with fodder that has a high nutrient concentration, like Ca, will have a high Ca concentration in their milk. Moreover, Ca has a strong interrelationship with the soil-plant-animal system (41).

The list of required minerals for plants is similar, but not identical, to that of humans. For instance, humans require Se and 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 (42).

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 (43). The toxicity and deficiency symptoms of different nutrients in humans are listed in Table 3 (44-51). 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 (52). 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 (53).

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 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 adversely 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. 2. 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 (54). 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 (55). Proper nutrient management in the soil exists only when soil health and quality are maintained. As we know, improper 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 (56).

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 animals and humans via plants. The goal was to assess the health of the environment and society by utilizing proper management practices at different levels of the food chain. A systematic study was conducted under the AICRP Project at Tamil Nadu Agricultural University in 2013 to assess the relationship within the soil plant animal continuum (57). Another study was conducted in Coimbatore, Tamil Nadu, based on the transfer of nutrients in various levels of the food chain and yield

Table 2. Deficiency and toxicity symptoms in animals (37, 38)

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	Leg abnormalities in poultry, growth retardation, milk fever in dairy cows, acidosis, and alkalosis.	Staggering gait, reduced Mg absorption.
Chlorine		
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, anaemia.	Diarrhoea, retarded growth, metabolic acidosis and even death.
Copper	Anaemia, scouring, skeletal deformity, aortic rupture, nervous disorder, change in coat and hair color pigments.	Haemolysis 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, hypoglycaemia, 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, goitre.	Hyperthyroidism, increased BMR, pulse rate, nervousness, and excitability.
Molybdenum	Rare.	Inhibits Cu absorption.
Chromium	Rare.	Rare.

variation due to different treatments (58). 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 (59). This study involved feeding rats with Zn-biofortified wheat grain cultivated on Zn-deficient soil through a combination of soil and foliar Zn application. In addition to soil treatment, treated sewage water can also serve as a nutrient source for amending soil deficient in nutrient content (60). The availability of nutrient content may vary across different ecological zones. An analysis conducted in the semi-arid region focused on certain micronutrients among indigenous sheep to identify the relationship between nutrient transfer from soil to the animal system (61). 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. A study is conducted in the feed, fodder, soil, and blood serum of dairy animals in the Sindhudurg District of Maharashtra, India (41). 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 in a subtropical hill agroecosystem (62). 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 in the Rohilkhand region of Uttar Pradesh to understand the interrelationship between soil and plant nutrient content, such as Zn, Cu, Co, and the fertility status of buffaloes (63). A study carried out in Haryana, India, which linked low copper levels in buffalo milk to correspondingly low copper levels in local soils and fodder (64). The different studies are shown in Table 4 (18, 57-64). 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

Table 3. Deficiency and toxicity symptoms in humans (44-51)

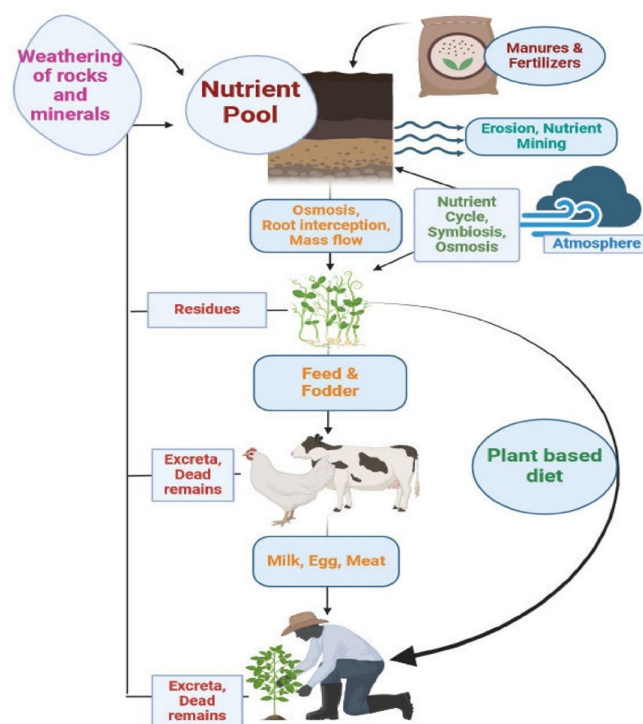
Mineral	Deficiency in human	Toxicity in human
Iron	Hypochromic microcytic anemia, reduced cognitive development, low birth weight, maternal anemia, puerperal sepsis, preterm birth	Constipation, gastrointestinal problems, organ damage
Zinc	Growth retardation, idiopathic primary osteoporosis, hair loss, 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

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 satisfying hunger 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 (65). South Asia has significantly higher rates of under nutrition 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 'South 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 (66). It is a serious problem; a multi-disciplinary approach is urgently needed,

**Fig. 2.** Nutrient flow in soil-plant-animal-human continuums.

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. 3 (67-75).

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' (76). 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 essential nutrients. This highlights the prevalence of hidden hunger in India, particularly among children and women, leading to issues such as anemia, stunted growth, and mental retardation (77). The hunger and malnutrition report, commonly known as the HUNGaMA report, released by the prime minister of India states that 42 % of children were malnourished and 59 % had stunted growth in a survey of 112 rural regions (78). 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 in the 10 most populated cities of India (79). The problem is not limited to calorie intake but also stems from factors such as lack of micronutrients, poor hygiene, marginalization of woman, and inadequate breastfeeding practices. Undernutrition is a global issue, contributing to high mortality rates among children under five (80). 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 (81). The different management practices that can be applied at different levels of the food chain are visualized in Fig. 4.

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 the quantity 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 S, 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 (82).

Agronomic fortification can be linked to the efficiency of NPK utilization by plants. It has been observed that certain micronutrients such as Zn, have a synergistic effect with macronutrient uptake by plants, and fortification of soil with micronutrients can enhance crop yield. Plant uptake of primary nutrients significantly increased with the different treatments of zinc fertilization in rice and increased crop yield and biomass (83).

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 (84). A notable example is the interaction between Zn and Fe. When both nutrients are supplied together, the production of siderophores by plants in the Poaceae family decreases, which reduces micronutrient uptake. The reduction in Zn concentration is observed when Fe is applied as fertilizer in rice and wheat cultivation, further solidifying the antagonistic interaction between these nutrients (85).

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 K 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 (86).

Vesicular-arbuscular mycorrhiza (VAM) and nutrient mobilization: Research shows that certain microorganisms can mobilize the nutrients present 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 wheat plants, VA-mycorrhizal plants consistently had greater amounts of phosphorus, copper, and zinc in their shoot dry matter compared to non-mycorrhizal plants (87). 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 (88).

Site-specific nutrient management: Precision agriculture focuses on site specific nutrient management (SSNM), which entails regulating soil nutrients differentially across

Table 4. Case studies related to the soil-plant-animal-human (18, 57-64)

Study area	Source of nutrients	Objective	Findings
Tamil Nadu Agricultural University	Fodder crop enriched with Zn nutrients	To analyze the significant relation of Zn in the soil-plant-animal continuum.	As a result of analysis of fodder, milk, dung, and blood, agro-nomic fortified fodder shows a significant rise in Zn 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 ($p < 0.05$) 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.

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



Fig. 3. Government initiatives (67-75).

(89).

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 (90). 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 (81). 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 (91).

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 (92). 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 (93).

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 (94).

Nipping and defoliation: Plants limit the accumulation of micronutrients in edible seeds through physiological and biochemical barriers. They use controlled homeostatic 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-

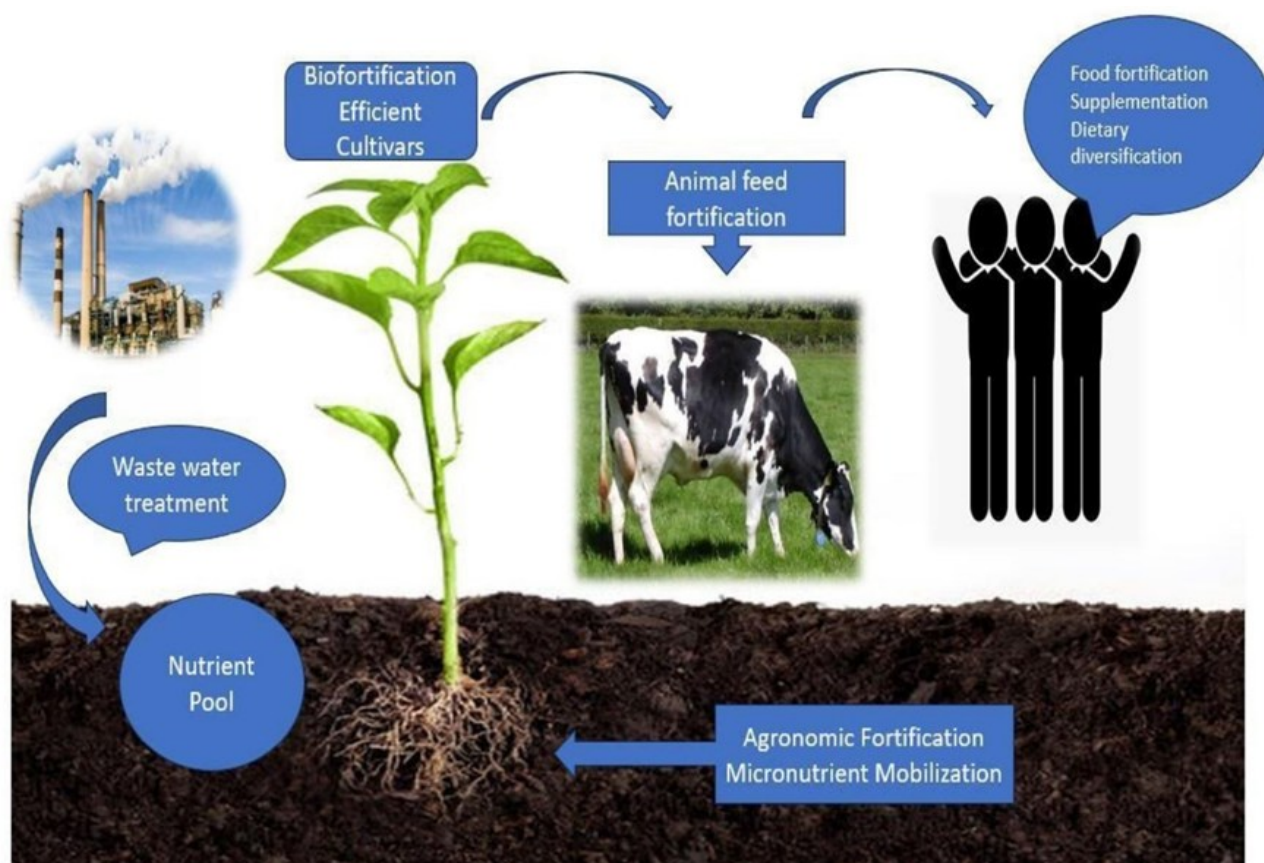


Fig. 4. Nutrient management practices in various levels of the food chain.

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 (91).

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 (95).

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 (96). 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 (97). 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 (98).

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 (99).

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 (100).

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 (101).

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 (102). 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 (103). 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 (104).

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.

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Author's contributions

Conceptualization was carried out by MS and SS. Resources were provided by ME, PC and VD. Data collection and visualization were performed by all authors. The original draft was written by MS and SS. 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.

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