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# Waste as a Sustainable Source of Nutrients for Plants and Humans: A Strategy to Reduce Hidden Hunger

**Teresa Rodríguez-Espinosa [1], Irene Voukkali [2], Ana Pérez-Gimeno [1], María Belén Almendro Candel [1], J. David Hernández-Martich [3], Antonis A. Zorpas [2], Ignacio Gómez Lucas [1] and Jose Navarro-Pedreño [1,*]**

[1] Department of Agrochemistry and Environment, University Miguel Hernández of Elche, Av. de la Universidad s/n, 03202 Elche, Alicante, Spain; maria.rodrigueze@umh.es (T.R.-E.); aperez@umh.es (A.P.-G.); mb.almendro@umh.es (M.B.A.C.); ignacio.gomez@umh.es (I.G.L.)

[2] Laboratory of Chemical Engineering and Engineering Sustainability, Sustainable Environmental Engineering, Faculty of Pure and Applied Sciences, Open University of Cyprus, Giannou Kranidioti 89, Latsia, Nicosia 2231, Cyprus; voukkei@yahoo.gr (I.V.); antoniszorpas@yahoo.com or antonis.zorpas@ouc.ac.cy (A.A.Z.)

[3] Botanical and Zoological Research Institute, Faculty of Science, Universidad Autónoma de Santo Domingo, Ciudad Universitaria, Santo Domingo 10105, Dominican Republic; jhernandez69@uasd.edu.do

* Correspondence: jonavar@umh.es

**Abstract:** Worldwide, over half of all preschool-aged children and two-thirds of non-pregnant women of reproductive age suffer from hidden hunger. This situation may worsen due to the expected increase in the world population and the effects of climate change. The objective of this paper is to conduct a review of the relationship between soil, plants, and humans at the nutritional level, factors that affect the availability of nutrients, and sustainable strategies to reduce hidden hunger from an organic waste utilization point of view. Nutritional deficiency in people begins with nutrient-deficient soil, followed by crops that do not meet humans' nutritional needs. According to previous studies, most agricultural soils are deficient in nutrients; however, organic residues containing high concentrations of minerals are present in the non-edible parts that are discarded. New opportunities (based on the circular economy strategy) are opening up to take advantage of the nutrient pool of organic residues, such as the preparation of substrates (technosols) or amendments. Their incorporation into the soil may consider various circumstances to ensure the mineralization and bioavailability of nutrients for crops. Several agronomic practices and methods to monitor soil and crop nutrient depletion can be considered among the best strategies to mitigate and reduce hidden hunger through determining which foods and which parts should be ingested, and how to process them to ensure mineral bioavailability.

**Keywords:** agri-food waste; food security; nutrient deficiency

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## 1. Introduction

The growing world population is expected to reach 9.8 billion in 2050 [1]. This will intensify the pressure on agriculture's capacity to meet the resulting agri-food demand [2,3]. The global food requirement is set to rise by a further 80–100% in 2050 [4] and will be a major challenge to ensure food and nutrition security. In 2022, around 2.4 billion people were moderately or severely food insecure, and in 2030, almost 600 million will be chronically undernourished [5].

A deficient nutrient intake is usually associated with an impossibility of acquiring food and the consequences are often visible such as undernourishment with a very low body weight. However, nutrient deficiencies also occur in the human body due to the intake of foods with an unbalanced nutritional content. The lack of micronutrients can occur without clinical manifestations, which is called hidden hunger [6,7]. For this reason, it is difficult to establish the incidence of hidden hunger. However, a recent global study estimated that 372 million preschool-aged children and 1.2 billion non-pregnant women of reproductive age suffer from micronutrient deficiencies [7]. Although the prevalence was found to be higher in low- and middle-income countries, it also affects people in high-income countries (45% of preschool-aged children and 48% of non-pregnant women of reproductive age) [7]. Micronutrient deficiencies lead to health problems, depending on the type of micronutrient, such as an increased susceptibility to infections, birth defects, blindness, anemia, hypothyroidism, genetic disorders, compromised growth and cognitive development, and may even result in death [7,8].

Soils are crucial for nutrient cycling and food security because they are where crops grow and absorb a large part of the available nutrients. The soil must be healthy to ensure its functionality in nutrient cycling and to facilitate crop growth, yield, and nutritional content [9]. Currently, the soil situation in Europe is not promising, as soils are a non-renewable resource in the short term and 60–70% of European soils are degraded [9,10]. In addition, agricultural soils also suffer from nutritional deficiencies on a global scale [11]. This leads to a detriment in the provision of environmental services from soils, affecting their capacity to produce food and the availability of nutrients for crops, among other factors, leading to the occurrence of deficiencies in micronutrient intake in the world's population, due to the lower nutrient concentrations in foodstuffs [12].

Several strategies can be addressed in this respect, notably, sustainable management in the agricultural and livestock sector and the use of its own waste as a nutritional source, in line with the circular economy [13]. According to Kummu et al. [14], the non-utilization of food waste implies the loss of around one-quarter of water resources, cropland, and fertilizers consumed during cultivation. Scherhaufer et al. [15] found that 15–16% of the total environmental impact of the food supply chain in Europe can be attributed to food waste (edible and inedible parts) and Read et al. [16] found this figure to be 16–18% in the United States. Furthermore, agricultural and livestock wastes contain enormous amounts of nutrients, but their disposal means the loss of a potential nutritional source [17–19]. In China, 0.29 kg phosphorus and 2.45 kg nitrogen per capita are lost through food waste [20]. In the United States, 880 mg of potassium per capita per day was lost due to food waste (retail and consumer) in 2012 [21]. At a global scale, 273 kcal of energy (calories) is embedded in the food waste generated per person per day, which represents ~15% of the global median daily dietary recommended intake value. Moreover, the amount wasted of the micronutrients zinc, copper, manganese, and selenium was as high as 25–50% of their daily requirements [22].

In addition to it being an ancestral practice, the use of waste as a raw material for soil construction (technosols) is also of recent interest [23–26]. The lack of fertile soil [10] can be compensated for by the development of technosols [27–29]. Previous studies confirm that technosols made from waste can accommodate crops and can provide the same or more environmental services than natural soil [23,24,30–32].

Therefore, the incorporation of these organic residues into the soil can favor yield. However, several factors influence whether the nutrients present in organic residues can be absorbed by plants and finally assimilated and utilized by the human body. The objective of this paper is to study the relationship between soil, plants, and humans at the nutritional level, factors that affect the availability of nutrients, and strategies to reduce hidden hunger from an organic waste utilization point of view.

## 2. Materials and Methods

The inclusion criteria established to determine whether an article could be admitted to the literature review were as follows: (i) research/papers/studies related to waste-derived nutrients as a sustainable source of nutrients and their relationship with hidden hunger; (ii) articles published from 1980 up until today; (iii) methodical demonstration and synthesis of findings; (iv) studies with a global geographical scope, which are given priority, although in cases where there is not a large sample, studies with a national or regional scope are included; (v) research mentioning comprehensive outcomes and/or information/data for an integrated approach to the topic under study; (vi) records identified using the keywords chosen by the authors.

To obtain the literature used for the bibliographic review, the main objective was to carry out documentary research, that is, to collect existing information on a topic or problem. The Scopus database was consulted as well as the available tools. The search options were title, abstract, and keywords. The following keywords were used (combined or separately): *hidden hunger*, *food security*, *food system*, *nutrients*, *minerals*, *micronutrients*, *human nutrition*, *crop nutrition*, *mineral nutrition*, *soil*, *nutrient requirement*, *nutrient deficiency*, *nutrient toxicity*, *mineralization*, *bioavailability*, *solubility*, *concentration*, *strategies*, *organic waste*, and *circular economy*.

## 3. Results and Discussion

### *3.1. Three Dimensions of Hidden Hunger: Soil, Crops, and Humans*

Food insecurity affects not only those who are hungry, but also those who, even when food is available, do not ingest the nutrients needed by the human body. Food insecurity therefore also encompasses the cases of people who are malnourished due to a deficiency, excess, or imbalance of macro- or micronutrient intake. Thus, the nutritional quality of the food ingested is also a key issue. The presence of multiple micronutrient deficiencies is often described as hidden hunger because it shows non-specific symptoms, which makes diagnosis difficult [6,7]. Some symptoms of micronutrient deficiency are specific to a specific disease or nutrient deficiency. However, others do not have specific clinical signs and are therefore more complicated to diagnose [33]. Worldwide, over half of preschool-aged children and two-thirds of non-pregnant women of reproductive age suffer from hidden hunger [7]. The most deficient micronutrients in diets are iron, zinc, iodine, and selenium. In addition, calcium, magnesium, and copper are also deficient nutrients [34].

Nutrient deficiency is a complex phenomenon, with interrelated causes, such as a limited capacity to acquire vegetables and fresh products, lack of information or education on dietary practice, changes in consumption habits, and degradation of ecosystems, especially soils [34,35]. Soils are the main reservoir of nutrients required by crops and people [36]. A soil with an unbalanced concentration of nutrients will lead to a lack or excess of nutrients in crops and subsequently in people [12]. Worldwide, 49% of soils are deficient in zinc, 31% in boron, 10% in manganese, and 3% in iron [36]. It should be noted that two of these minerals are also considered deficient in the human diet, as mentioned above.

Food and nutrition security aims to “achieve all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” [5,37]. Food security therefore encompasses several aspects, such as food availability and physical accessibility, people’s purchasing power, and healthy and balanced food consumption, as well as ensuring that these attributes are maintained over time for the stability of the system. However, studies have concluded that an environmental and a citizen empowerment dimension in agricultural systems must also be added [35]. The consequences of climate change (heat waves, drought, floods) and environmental impacts on agricultural and natural environments are a destabilizing factor for the food system [38–40]. Therefore, to ensure the long-term continuity of this system, sustainability must be part of the equation too (Figure 1).

A sustainable food system is defined as a “system that delivers food security and nutrition for all in such a way that the economic, social, and environmental bases to generate food security and nutrition for future generations are not compromised” [41]. The environmental impacts associated with the food sector are considerable and diverse: deforestation and biodiversity loss, soil quality modification, resource consumption, nutrient loss, ecosystem degradation, and waste production [42–47].

Human, crop, and soil nutrient depletion is expected to become worse due to the increase in soil degradation and the consequences of climate change [11,48–50]. The consequences of climate change will affect food production and the nutritional content of many crops, leading to a reduction of 3 to 17% in protein, iron, and zinc concentrations [48,49].

This implies an expected growth of the world population suffering from hidden hunger, based on the 2050 estimated projections for both the population and $CO_2$ emissions. Zinc and protein depletion will affect between 122 and 175 million people, whereas iron deficiency will affect 1.4 billion women of childbearing age and children under 5 [50]. Furthermore, climate change simulations predict changes in the bioavailability of nutrients in soils. Worldwide, calcium, magnesium, and potassium are the most bioavailable nutrients, and their bioavailability is biome-dependent and can be modified by agriculture practices [51].

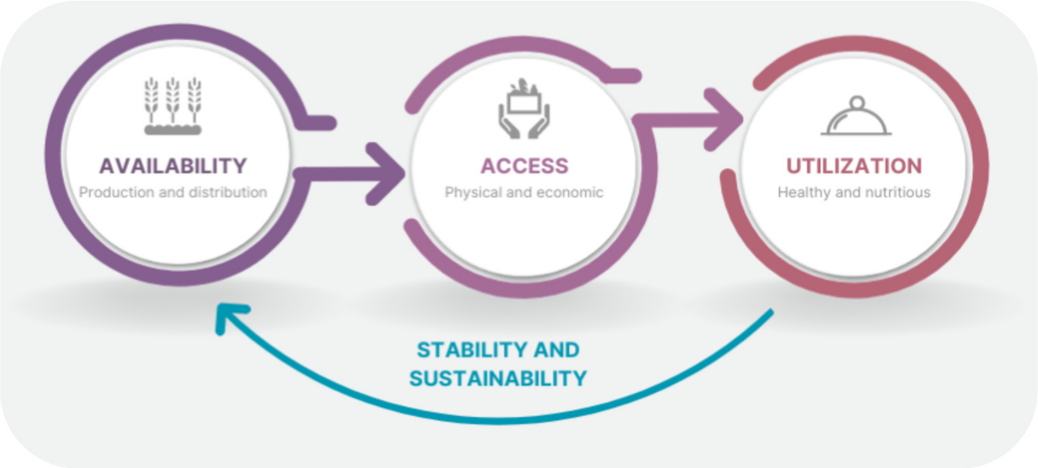

**Figure 1.** Sustainable food system for food security.

Therefore, soil nutrition, crop nutrition, and human nutrition are interrelated, as shown in Figure 2, to such an extent that the nutritional quality of plant-based foods depends on the health and quality of soil [36].

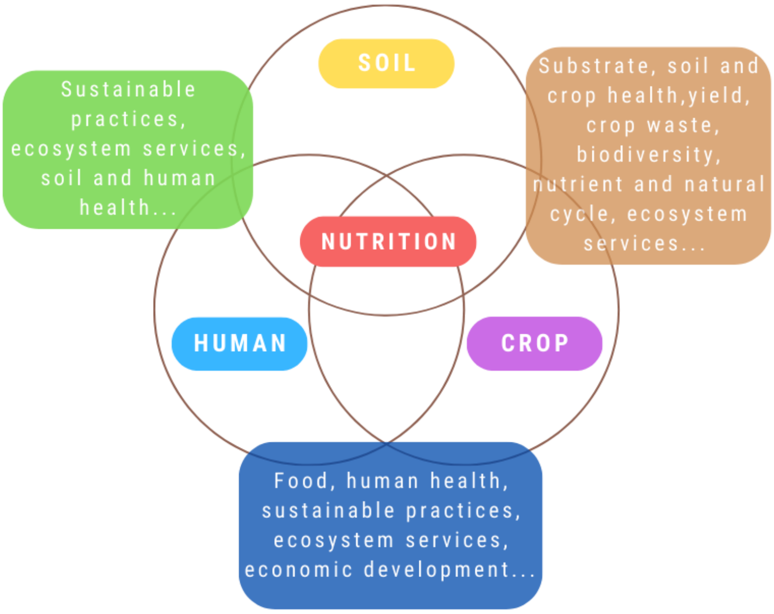

**Figure 2.** Three dimensions of nutrition: soil, crops, and humans.

### 3.2. Mineral Nutrient Requirements for Humans

A healthy human diet requires the adequate intake of diverse nutrients. Most of them come from the ingestion of plant-based foods (63% of proteins, 81% of iron, and 68% of zinc) because they cannot be synthesized by the human body [50]. The human body needs between 40 and 49 essential nutrients like minerals, vitamins, carbohydrates, amino acids, and fatty acids that are vital for metabolic and physiologic functions [52,53]. In addition to water, humans require macronutrients (required daily intake > 100 mg) and micronutrients (required daily intake < 100 mg) [54]. Minerals are needed in the human body for metabolic processes and homeostasis, brain and muscle function, bone structure, and immune and reproductive systems, among others [36,55]. Table 1 shows the mineral nutrients that humans need to remain healthy.

**Table 1.** Minerals needed for good human health.

| | **Nutrients** | **References** |
|---|---|---|
| Macronutrients | N, P, Na, K, Ca, Mg, S, Cl | Garg et al. [52]; Welch and Graham [53];<br>Gharibzahedi and Jafari [55];<br>Oliver and Gregory [56] |
| Micronutrients | Fe, Mn, Cu, Zn, I, Se, Mo, Co, Ni, F, B, Cr, V, Si, As, Sn | |

The unbalanced consumption of any nutrient, either in excess or deficiency, can lead to health problems like scurvy, rickets, anemia and impair the functionality of the main systems of the human body: nervous, digestive, immune, epidermal, reproductive, and skeletal [36,57]. Poor micronutrient intake can contribute to increased morbidity and mortality rates in infants and children, and can limit their ability to learn and grow. The population groups most exposed to the negative effects of micronutrient malnutrition are women (between 15 and 49 years of age, pregnant and lactating women) and young children, due to their high intake requirements [7,53,58]. In addition, the micronutrient requirements of the human body change over the course of the human life cycle; growth phases, gender, diseases, metabolic changes, and lifestyle can be factors that affect individual needs [57].

Scientists have defined the recommended dietary allowances (RDAs), the adequate intake (AI), and tolerable upper intake level (UL) for minerals in the human body (Table 2). As the mineral intake increases above the UL, so does the risk of disease. The bioavailability of nutrients ingested with food can be highly variable and previous studies have highlighted nutritional deficiencies in the general population [7]. So much so, 57% and 29.2% of U.S. citizens do not meet the intake values for Mg and Zn, respectively, and are estimated to meet the needs of only half of all healthy individuals (from the age of 1) [57].

The nutrient supply depends not only on the quantity and quality of food, but also on the amount of nutrients that can be absorbed and are finally available for physiological functions or storage (bioavailability). The metabolic processes that nutrients undergo are digestion, solubilization, absorption, uptake and release, enzymatic transformation, secretion, and excretion [59]. In general, the bioavailability of macronutrients is higher than that of micronutrients [60]. Table 3 shows bioavailability data collected for various mineral nutrients. It can be seen that for each element there is a large variability among food sources. Furthermore, the bioavailability of nutrients can be affected by other factors, such as food handling practices like selecting parts of the vegetable, cooking, storage, transport, and processing, as well as the presence of substances that inhibit or enhance absorption and competition for transport proteins or absorption sites [52,55,59,61,62]. In addition, the bioavailability of mineral nutrients can be affected by the chemical form in which the nutrient is present. For instance, the most commonly ingested form of Fe is one of a low bioavailability [60], and its absorption depends on the presence of other elements in the ingested food. The presence of Cu enhances Fe absorption, whereas the presence of Ca may have the opposite effect [56].

**Table 2.** The recommended dietary allowances (RDAs), the adequate intake (AI), and tolerable upper intake level (UL) of minerals (mg day$^{-1}$) for adults.

| | **P** | **Na** | **K** | **Ca** | **Mg** | **Cl** | **Fe** | **Mn** | **Cu** | **Zn** | **I** | **Se** | **F** | **Mo** | **Cr** | **B** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RDA [a] | 1200 [d] | 500 [d] | 2000 [d] | 1200 [d] | 350 [d] | 750 [d] | 15 [d] | | | | | | | | | |
| AI [b] | 550 [f,g] | | 3500 [f,g] | 950 [g] | 300–350 [f,g] | | 8–18 [d] | 2–5 [d], 3 [f] | 1.5–3 [d] | 7.5 [g], 8–11 [e], 15 [d] | 0.15 [d–g] | 0.07 [d,f] | 1.5–4 [d], 2.9–3.4 [f] | 0.075–0.25 [d], 0.45 [e], 0.065 [f] | 0.05–0.2 [d] | |
| UL [c] | | | | 2500 [f] | 250 [f] | | 45 [e] | | | 25 [f], 40 [e] | 1.1 [e], 0.6 [f] | 0.3 [f] | 7 [f] | 2 [e], 0.6 [f] | | 10 [f] |

[a] Recommended dietary allowances (RDAs) are the daily levels of intake of essential nutrients judged to be adequate to meet the known nutrient needs of all healthy persons. Values presented are the highest RDAs either for male or female adults, excluding pregnant or lactating women [63]. [b] The adequate intake (AI) is a value based on experimentally derived intake levels or approximations of observed mean nutrient intakes by a group (or groups) of healthy people [64]. [c] The tolerable upper intake level (UL) is the highest level of daily nutrient intake that is likely to pose no risk of adverse health effects for almost all individuals in the specified life stage group [64]. [d] [63]; [e] [64]; [f] [65]; [g] [59].

**Table 3.** Availability of mineral nutrients according to food source (%).

| | **K** | **Ca** | **Mg** | **Fe** | **Cu** | **Zn** | **I** | **Se** |
|---|---|---|---|---|---|---|---|---|
| Milk [a] | | 40 | 24–75 | | | 25–30 | 90 | |
| Vegetables and fruit | 60–85 [a] | 20–40 [a], 5–41 [b] | 23–35 [a] | 12 [a] | | | | |
| Mixed food [b] | | 20–45 | 10–75 | | 25–70 | 20–40 | 100 | 50–95 |

[a] [59]; [b] [66].

### 3.3. Mineral Nutrient Requirements for Plants

Plants need oxygen, carbon, and hydrogen and other elements to complete their life cycle. An element is essential if a plant cannot complete its life cycle in the absence of that element. Essential mineral nutrients for most plants are shown in Table 4. In addition, nickel (Ni), silicon (Si), sodium (Na), cobalt (Co), and vanadium (V) are essential for some plants [67]. However, other mineral elements are considered beneficial because they are essential for some plant species under certain conditions. Sodium (Na), selenium (Se), cobalt (Co), aluminum (Al), iodine (I), and silicon (Si) are considered beneficial to some plants [56,68].

**Table 4.** Essential minerals for plants.

| | Nutrients | References |
|---|---|---|
| Macronutrients | N, K, Ca, P, Mg, S | FAO [36]; Oliver and Gregory [56]; Kirkby [68]; |
| Micronutrients | Fe, Cl, Mn, Zn, B, Cu, Mo | Rengel [69]; Bell and Dell [70]; White and Brown [71] |

As in humans, high or low concentrations of minerals have consequences for the development and functioning of plants and consequently on yield [68,71], which is more significant for micronutrients. Mn is needed for plant metabolism, and its deficiency is common, causing a biomass reduction [72]. The toxicity caused by an excessive amount of Mn varies considerably, depending on the plant species. Fe is a key nutrient in the redox system and its deficiency triggers the inhibition of chloroplast development and of root elongation. The main consequence of high Fe concentrations in plant tissues is a negative effect on crop yield [73]. Cu is required for the performance of major plant systems, and its toxicity can come from the use of fungicides, industrial activities, and the application of animal slurries [74,75]. The presence of small and poorly developed leaves may be a symptom of a lack of Zn, since the root grows at the expense of the aerial parts [76]. Generally, Ni excess is more of a concern than its deficiency. In agricultural soils, the application of soil amendments like manure and compost can alleviate high Ni concentrations in crops [77]. The shortage of B implies problems with the growth and development of leaves, flowers, and fruits, as well as necrosis. Frequent manuring of the soil with municipal compost may mask B toxicity in certain crop species [75].

Plant growth (dry matter production) is linked to nutrient supply. Initially, as nutrients are supplied, plants rapidly increase their biomass if there is not a large variation in nutrient concentrations until reaching the phase in which their growth is maximum and is less affected by changes in nutrient supply [78]. If the nutrient supply continues to increase, the plant experiences a decline in growth due to toxicity [79]. Alternatively, a temporary interruption or reduction in the required amount of nutrients leads to nutritional deficiencies. In general, nutrient deficiency symptoms in plants have to be severe to be noticeable, such as reduced growth and yield [78,79].

Due to their relevance, the concentrations of minerals in plant tissues that are optimal for maximum plant growth have been studied and regarded as "concentrations for adequate plant growth or sufficiency" [78]. However, it is convenient to consider the margin of reduction in concentration of the nutrient in which the plant is deficient; this is known as "the critical deficiency range" [80]; this is the nutrient concentration that allows 90% or 95% of the maximum shoot dry matter [78,81], or 90% of the maximum yield [71]. Once this threshold is exceeded, the deficiency zone is reached where growth is drastically reduced.

In addition, the mineral concentration in a diagnostic tissue above which the yield is decreased by more than 10% is known as "the critical toxicity concentration" [78,82]. When nutrient concentrations in tissues are below the critical concentration deficiency, various plant symptoms are observed depending on the nutrient and species tolerance [75]. Table 5 compiles the nutrient concentrations suitable for plant growth as well as critical concentrations for deficiency and toxicity. For more details on these concentrations, the main agricultural plants and their growth phases can be found in López [83] and Riechelman et al. [84].

Several aspects can contribute to the fluctuation of nutrient deficiency, sufficiency, and toxicity ranges, such as nutrient interactions, plant genotype, developmental stage, plant part, and environmental conditions [52,78,79]. When the concentration of a nutrient reaches the range of toxicity, it can lead to a deficiency of other nutrients, due to synergism and antagonism [84]. The fact that nutrients are in the soil does not mean that plants can absorb them. In fact, the available nutrient content in soils is limited to a small fraction of the total content. The bioavailability of minerals depends on several factors like the health of the soil and environment, soil management practices, and the proper physical, chemical, and biological conditions of soil for the cycling of nutrients and their transformation to the chemical forms that roots require to absorb them. Plants have developed mechanisms for the selection, transport, and accumulation of nutrients from all those available in the aqueous soil solution. As well as processes of adaptation and tolerance to limiting or excessive concentrations of mineral nutrients, the mineral chemical form is also crucial for its transport through plant tissues [36,68,85].

As the plant advances in its life cycle, its nutrient needs are lower, except those for Ca and B [78]. In addition, the nutrient concentration in cell tissues varies among plant types and plant parts, resulting in an uneven distribution of nutrients. For example, in the case of Fe in rice, a higher amount is observed in the leaves than in the polished grains [52]. If we want to improve our Ca intake, it is advisable to select vegetables like broccoli, which is one of its predominant sources. Wheat flour, pea, oat, and peanut seeds can be excellent sources of Mg, Fe, Zn, Mn, Cu, Mo, and Se [55,61]. Nevertheless, a proportion of each nutrient is immobilized in the inedible parts, as mentioned before.

### *3.4. Mineral Nutrients in Agricultural Soil*

Nutrient inputs and outputs into agricultural soils can be natural or caused by human activities. Ecosystems have a variety of nutrient inputs, such as atmospheric deposition, soil organic matter mineralization or mineral soil content. Nutrient outflows are produced naturally by leaching, erosion, volatilization, greenhouse gas emission, and plant uptake. However, in crop lands, human activities can affect these processes when using organic or mineral fertilizers [36].

To benefit the crop yield, the soil nutrients absorbable by plants must be present in adequate quantities and in their soluble forms in the soil during the cultivation stage [36,71]. A global study conducted in 2000 by Tan et al. [11] estimated that 59%, 85%, and 90% of harvested soils displayed a depletion of N, P, and K, respectively. However, no similar studies have been found on a global scale for micronutrient deficiencies. In Table 6, references are compiled showing the deficient nutritional status of agricultural soils at the national or local level. In China, 55% of arable lands are magnesium-deficient and in India, 58.6%, 51.2%, and 44.7% of the agricultural soils are sulfur-, zinc-, and boron-deficient, respectively [12,86]. Authors have reflected on the relationship between major soil groups and their propensity for a deficiency of certain micronutrients [36,70].

For plant nutrient absorption to be effective, soils must have adequate physical, chemical, and biological conditions, as well as favorable climatic conditions [87]. In addition, the input of organic matter or fertilizers and agricultural management practices significantly affect the nutrient pool in the soil [88–92].

**Table 5.** Mineral nutrient concentration for adequate plant growth, critical deficiency, and critical toxicity concentration.

| | Units | N | K | Ca | P | Mg | S | Fe | Cl | Mn | Zn | B | Cu | Ni | Mo | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean concentration for adequate plant growth [a] | mg kg$^{-1}$ dw | 15,000 | 10,000 | 5000 | 2000 | 2000 | 1000 | 100 | 100 | 50 | 20<br>50–60 [a,d] | 20 | 6<br>9–11 [a,d] | 0.1<br>2 [a,d] | 0.1 | Kirkby [68]; Davis and Beckett [93] |
| Range concentration for sufficiency [b] | mg g$^{-1}$ dw | 15–40 | 5–40 | 0.5–10 | 2–5 | 1.5–3.5 | 1–5 | 50–150 × 100$^{-3}$ | 0.1–6 | 10–20 × 10$^{-3}$ | 15–30 × 10$^{-3}$ | 5–100 × 10$^{-3}$ | 1–5 × 10$^{-3}$ | 0.1 × 10$^{-3}$ | 0.1–1 × 10$^{-3}$ | White and Brown [71] |
| | mg kg$^{-1}$ dw | | | | | | | 50–300 [b] | 100–1000 [b] | 25–250 [b] | 15–100 [b] | 15–150 [b] | 3–15 [b] | | 0.1–5 [b] | Guardiola and García [94] |
| Critical deficiency | mg kg$^{-1}$ dw | | | | | | | 50–150 [b];<br>200 [a] | | 10–20 [b] | 15–20 | 5–10;<br>20–70;<br>80–100 [d] | 1–5 | 0.01–10 | 0.015–0.05 | Bell and Dell [70]; Cakmak et al. [75]; Alloway [82]; Häussling et al. [95]; Reuter et al. [96]; Brown [97] |
| | µg g$^{-1}$ dw | | | | | | | | | | 15–0 [b] | | | | 0.1–1.0 [b] | Cakmak et al. [75] |
| | mg g$^{-1}$ dw | | | | | | | | 2 | | | | | | | Cakmak et al. [75] |
| Critical toxicity [b] | mg g$^{-1}$ dw | | >50 | >100 | >10 | >15 | | >0.5 | 4–7<br>>3.5;<br>20–30 [d] | 0.2–5.3 | 100–300 × 10$^{-3}$ | 0.1–1 | 15–30 × 10$^{-3}$ | 20–30 × 10$^{-3}$ | 1 | White and Brown [71] Cakmak et al. [75] |
| | mg kg$^{-1}$ dw | | | | | | | >500 [b] | | 200–300 [a,c] | | 100–1000 [b,d] | 14–25;<br>17–21;<br>15–22 [a,d] | | | Cakmak et al. [75]; Davis and Beckett [93]; Edwards and Asher [98]; Yamauchi [99] |
| | µg g$^{-1}$ dw | | | | | | | | | | 100–300 [b] | | | >10–>50 [d] | | Ruano et al. [100]; Asher [101]; Chaney [102] |

[a] In shoot system. [b] In leaves. [c] Vegetative parts. [d] Depending on plant tolerance.

**Table 6.** Nutritional deficiency in agricultural soils.

| Nutrient | Nutritional Deficiency | References |
|---|---|---|
| N | 12.5% in a vineyard after rainfall (Spain) | Ramos and Martínez-Casasnovas [103] |
| | 59% of harvested soils (worldwide) | Tan et al. [11] |
| K | 10.2% in a vineyard after rainfall (Spain) | Ramos and Martínez-Casasnovas [103] |
| | 90% of harvested soils (worldwide) | Tan et al. [11] |
| | 88.11% in green sugarcane harvesting compared to burnt (Brazil) | Gabarra Mendonça et al. [104] |
| Ca | 81.59% in green sugarcane harvesting compared to burnt (Brazil) | Gabarra Mendonça et al. [104] |
| P | 60.5% in a vineyard after rainfall (Spain) | Ramos and Martínez-Casasnovas [103] |
| | 85% of harvested soils (worldwide) | Tan et al. [11] |
| | 78.87% in green sugarcane harvesting compared to burnt (Brazil) | Gabarra Mendonça et al. [104] |
| Mg | 81.40% in green sugarcane harvesting compared to burnt (Brazil) | Gabarra Mendonça et al. [104] |
| | 55% in arable lands (China) | Ishfaq et al. [86] |
| S | 60–100% in watersheds (India) | Rego et al. [105] |
| | 58.6% in agricultural soils (India) | Shukla et al. [12] |
| Fe | 19.2% in agricultural soils (India) | Shukla et al. [12] |
| Mn | 17.4% in agricultural soils (India) | Shukla et al. [12] |
| Zn | 81–100% in watersheds (India) | Rego et al. [105] |
| | 51.2% in agricultural soils (India) | Shukla et al. [12] |
| B | 0–100% in watershed (India) | Rego et al. [105] |
| | 44.7% in agricultural soils (India) | Shukla et al. [12] |
| Cu | 11.4% in agricultural soils (India) | Shukla et al. [12] |

Organic matter decomposition and mineralization are mechanisms that nature employs for the cycling and supply of nutrients. Mineralization processes performed by soil microorganisms transform organic compounds into water-soluble inorganic forms of nutrients, needed by most plants. The key factor for the mineralization of organic matter present in organic wastes is the C/N ratio, which depends on the composition of each type of waste. The potential C/N ratio that favors mineralization is between 20 and 30 [106,107], which represents an equilibrium between N mineralization and microbial immobilization. Lower ratios favor the rapid release of nutrients, whereas higher ratios slow it down. Organic waste has a diverse C/N ratio. Non-manure animal wastes, animal manures, compost, sewage sludge, and municipal solid wastes usually have low C/N ratios, between 1 and 17, but these could be up to 29. On the contrary, organic residues from pruning and harvesting show high C/N values (from 44 to 139) [107–111].

Agricultural production may trigger a depletion in the concentrations of soil nutrients, which has to be counterbalanced by their supply. In sub-Saharan Africa, erosion and crop harvest (edible and residue) were the cause of about 70% of all N losses, nearly 90% of all K losses, and 100% of the P losses [112]. Organic residues remaining in or added to the soil can replenish nutrients but can involve some challenges. One challenge is logistical, due to the high number of residues needed to meet crops' demand for nutrients, which has been estimated for N to be from 70.59 to 515.65 tons per hectare f.w. of pruning and harvesting residues [111]. Organic waste has large amounts of nutrients, which make it an excellent source of nutrients [113]. Another challenge is the synchronization of the period of release of each nutrient with the stage of crop development in which it is required [114]. In addition, the presence in organic wastes of nutrients that are heavy metals can lead to problems for ecosystems, plant development, and human health [36,115]. However, its use has great advantages, such as improving soil properties, fertility, microbial biomass, and carbon storage, as well as enhancing ecosystem functioning and circular economy strategies [115–120].

The application of inorganic fertilizers quickly provides a supply of nutrients with a high mineralization rate. However, their manufacture requires the extraction and consumption of non-renewable resources, affects microbial activity, and can lead to environmental pollution (e.g., by leaching), soil degradation, and soil organic carbon and nitrogen reduction [121–124].

When organic residues have high C/N values, their mineralization requires an additional nitrogen input. In agricultural systems, this comes from the mineralized nitrogen found in the soil or from fertilizers. In either case, the bacteria will prefer the inorganic nitrogen already available in the soil, which they will immobilize to meet their metabolic needs; thus, they compete with plants for this nutrient. This decrease in the nitrogen content available in the soil can lead to nutritional deficiencies for crops. As a consequence, the bacterial mineralization of organic matter is relegated until new sources of nitrogen are found, for example, with fertilizers [91,107,111]. Therefore, to achieve adequate fertilization, a combination of organic and inorganic fertilization systems is appropriate if their adverse effects are kept to a minimum [36,111,118,125].

### 3.5. Mineral Nutrients and Circular Economy

While nature shows a constant cycle of activity, humans show a preference for linear activities. This is because of the time scale on which each of them functions; it is long-term for nature, whereas it is generally short-term for humans. To achieve sustainability, it is essential to achieve a balance between them. Therefore, it is desirable to gear human interests towards circularity. In the agricultural sector, the application of circularity or a circular economy is understood as "the set of activities designed to not only ensure economic, environmental and social sustainability in agriculture through practices that pursue efficient and effective use of resources in all phases of the value chain, but also guarantee the regeneration of and biodiversity in agroecosystems and the surrounding ecosystems" [126]. The environmental impacts associated with agricultural production are diverse and considerable, as stated before. Each stage of agricultural production involves resource consumption (e.g., nutrients, water, energy, seeds, soil occupation, and pesticides), outputs (e.g., nutritious food, waste, emissions, and contaminated waste), and associated impacts (e.g., reduction in the soil nutrient content, soil degradation, and greenhouse gas emissions). It is undoubtedly a field of growing interest among the scientific community [42,47,119].

This work focuses on the need to apply the circular economy to nutrient management to obtain foods with adequate nutrient concentrations. To achieve this circularity, we must (a) enhance the efficient use of resources, mainly non-renewable resources, such as nutrients, safeguarding their adequate dosage and replenishment; (b) ensure that nutrient flows are kept in a loop to avoid leaches and immobilization (e.g., reincorporating into soil organic matter produced as food losses and waste, pruning residues, and animal manures); (c) guarantee agricultural sustainability in its three dimensions: environmental, economic, and social [45,111,127,128]. The global cycles of the main macronutrients (nitrogenous, phosphorous, and potassium) have been extensively described; however, not so much for micronutrients [36,70,89,129]. This is because agriculture has focused on providing the macronutrients most needed to increase yield, but not on ensuring the presence of micronutrients in food [52]. Nutrient inputs into agricultural systems are produced by the incorporation of organic matter or inorganic fertilizers, the latter being the most common way. In 2022, the projected demand for nitrogen, phosphorus, and potassium as fertilizers was 200,919 thousand tons [130]. For ages, farmers have been using organic waste generated from their activities as organic matter for the soil. Nowadays, only 2% of usable resources are reused in farms, and 98% becomes waste and pollutants [131,132].

Losses (from harvest/slaughter/catch) and waste (a the retail and consumption levels) of edible food are produced throughout the food chain [133]. According to the FAO [134], the amount of lost or wasted edible food produced for human consumption worldwide is about 1.3 billion tons per year, accounting for one-third of the total production. More recently, the FAO [133] measured 14% of the food produced globally as being lost from the post-harvest stage onward. This phenomenon occurs in both developed (more than 40% of the food losses occur at the retail and consumer levels, being 222 million ton) and developing countries (more than 40% of the food losses occur at the post-harvest and processing levels). These food losses result in an aggravation of the environmental impacts generated during the production and distribution process, as well as a hindrance to the sustainability of the system and food and nutrition security. The flow of global nutrient losses in food production was estimated by Berners-Lee, et al. [129]. Their findings indicate that 11 mg per person per day of iron is lost and 8 mg per person per day of zinc is lost due to harvest losses, post-harvest losses, investment, and non-food uses.

In addition, livestock and agricultural farms produce other types of non-edible organic waste, through activities such as pruning, cleaning or removal of weeds, straw, litterfall, and animal manure. Although that type of waste from farms is of increasing interest for nutrient recovery [135–137], it is generally destined for landfill or burning. These practices have consequences for the environment since greenhouse gases are emitted into the atmosphere, carbon sequestration is reduced, the risk of fire increases, and there is a loss and flow change of the elements and nutrients that compose them [69,106,107,138].

In sustainable and organic farming, organic residues are applied to soil as a nutritional source for crops and humans to improve the soil's physical properties, to increase carbon storage, and to improve the microbial activity, biodiversity, and circular economy, among other factors [10,116,117,138–145]. Moreover, this practice maintains nutrient circles. Circularity in the agricultural and food sector is achieved when all organic waste produced at any stage (cultivation, harvest/slaughter/catch, processing, distribution, and consumption) is recovered and incorporated as raw material (Figure 3). These organic residues can be incorporated into the soil or used to build technosols, facilitating the indefinite use of nutrients by plants.

**Figure 3.** Circularity diagram of the agricultural sector.

### *3.6. Waste-Derived Nutrients as Mineral Nutrient Source*

Organic waste has large amounts of nutrients, which makes it an excellent source of nutrients [113]. According to Fortunati et al. [146], the UE generated about 700 million tons of agri-food waste. In the study conducted by Caldeira et al. [147] in the same region, the distribution of waste, including the primary production, processing and manufacturing, distribution and retail, and consumption of edible and inedible food, corresponded to 51% fish, 46% vegetables, 41% fruit, 36% oil crops, 29% eggs, 23% meat, 22% potatoes, 20% cereals, 5% dairy, and 4% sugar beets. Furthermore, they highlighted the large number of residues of inedible parts generated in the consumption phase, at 40 to 49% of the waste flow for fruit and vegetables. As for meat, 80% of the waste produced in the processing and manufacturing phases is composed of inedible parts, but it is not considered waste since it is used in other industries. However, during other phases of agricultural activity, non-edible residues, from pruning and leaf fall, are also generated.

The amount of crop residues generated during the primary production phase varies depending on the type of species. Thus, the amount of residues generated after harvesting roots and aerial debris (stubble) is between 1.11 and 2.44 tons per hectare for root crops, 2.88 and 3.89 tons per hectare for legumes, 3.38 and 5.60 tons per hectare for cereals, 4.67 and 4.03 tons per hectare for forage crops, and 7.01 and 14.32 tons per hectare for oilseed crops. Sugar beet (1.11 tons per hectare) and winter rape (14.32 tons per hectare) are the crops that generate, respectively, the lowest and the largest amounts of residues per hectare among 17 crops studied by Torma et al. [148] in Slovakia.

It should be emphasized that nutrients are not only lost through food waste but also by discarding inedible foods. The fraction of nutrients absorbed from the soil and stored in the non-food parts of the crop has been studied little since it has been considered as waste instead of yield profit and a source of raw material like mineral nutrients. De Mello Prado [149] reported the amounts of N, K, Ca, P, Mg, S, Fe, Mn, Zn, B, Cu, and Mo found in the edible (grain) and inedible (residue) parts of wheat and soybeans. The most abundant nutrients in the inedible components of wheat were K (87%), Ca (81%), Fe (72%), Mn (70%), B (67%), and S (64%), whereas in the soybean residues, they were Ca (84%), Mg (77%), Fe (75%), B (69%), and Mn (67%).

Wastewater is also a source of nutrients, the type and amount of which can vary with the wastewater origin, being industrial, human, or animal [150]. Each year, one person contributes 3 kg N to domestic wastewater [113]. Thus, based on population growth estimates [1], in 2050, we could have an overall contribution of 29.4 million tons of N. Pig and cattle manure wastewaters contain three times more N than domestic wastewater [113]. In the EU, the total sewage sludge produced from urban wastewater (in terms of dry substances) was 2372.62 thousand tons in 2021 [151]. During the year 2000, throughout the EU, 661.58 thousand tons (dry matter) of sewage sludge was used in agriculture. Spain is one of the countries that uses the most sewage sludge to recover the nutritional value of crops (80%) [152].

The fishing industry also generates high amounts of organic waste; this amounted to 50 to 125 million tons worldwide in 2018 [153]. Of the total fish caught, 70% requires processing and 20 to 80% becomes waste depending on the type of species and the final product [154]. Fish waste is either used for feeding aquaculture organisms, fishmeal and oil production, or is eliminated [154]. Aquaculture also generates fish sludge composed of water, fish feed, fecal matter, and biomass from dead fish and/or other species. This sludge has a high nutritional content depending on the species being bred [153,155]. The worldwide aquaculture production was 87.5 million tons in 2020. The weight of fish sludge generated per ton of fish produced was estimated at 1.4 tons by Celis et al. [156]. This translates to a release of nutrients into the environment estimated at 9000 tons of P and 27,000 tons of N per year in Norway [157]. Further, dried fish sludge can be used as a fertilizer, being able to replace 50 to 80% of the N in mineral fertilizers [158].

Table 7 provides the nutrient concentrations obtained in several types of waste from previous studies.

**Table 7.** Mineral nutrient concentrations in organic waste.

| Waste | Units | N | K | Na | Ca | P | Mg | S | Fe | Mn | Zn | B | Cu | Ni | Mo | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Animal manure | mg kg$^{-1}$ | | | | | | | | | | 65.4–214.2 | | 16.6–59.2 | | 1.5–4.9 | Ramos et al. [159] |
| Animal manure | g kg$^{-1}$ dw | 12.3–37.7 | 5.6–35.4 | | | 0.9–10.4 | | | | | | | | | | Adiaha [160] |
| Aquaculture manure waste | mg kg$^{-1}$ dw | | | 131–614 | | | | | 547–25,206 | 87–3349 | | | | | | Shi et al. [155] |
| Crop residue | mg kg$^{-1}$ | | 18.08–41.50 | | 3.47–13.41 | 2.29–6.58 | 2.62–11.41 | 0.48–0.93 | 0.43–2.73 | 0.06–0.20 | 0.11–0.27 | | 0.03–0.05 | | | Yusuf et al. [161] |
| Fish sludge (liquid part) | mg kg$^{-1}$ | 33.1–53.8 | 16.6–36.7 | | 26.6–173.4 | 17.1–43.9 | 7.4–39.4 | 7.4–243.3 | 0.03–0.1 | 0.09–0.3 | 0.1–0.02 | 0.03–0.06 | 0.01 | | | Goddek et al. [162] |
| Fish sludge (solid part) | mg kg$^{-1}$ | 177.1–362.6 | 8.3–27 | | 239.1–274 | 133.2–149.8 | 20.3–22 | | 9.9–18.7 | 1.4–2.3 | 4.9–7.1 | 0.5–0.9 | 0.4–0.7 | | | Goddek et al. [162] |
| Fish waste | mg kg$^{-1}$ dw | | | | | | | | | | | | | 2.78 | | Illera-Vives et al. [163] |
| Marine waste compost | mg kg$^{-1}$ dw | | | | | | | | 907 | 87.30 | 31.4 | | 5.62 | 3.60 | | Illera-Vives et al. [163] |
| Pruning residue | mg kg$^{-1}$ dw | 4400–9300 | 1648–6889 | 160–1079 | 6861–14,059 | | 924–2259 | | 44–371 | 5.7–32.2 | 4.6–19.4 | | 3.8–8.2 | | | Rodríguez-Espinosa et al. [111,114] |
| Seaweed | mg kg$^{-1}$ dw | | | | | | | | | | | | | 3.73 | | Illera-Vives et al. [163] |
| Sewage sludge compost | mg kg$^{-1}$ dw | 22,600 | 4585 | 1529 | 64,245 | | 5815 | | 18,989 | 94.4 | 249.5 | | 79.7 | 6.2 | | Rodríguez-Espinosa et al. [111,114,115] |

Many studies conclude that waste is a suitable source of nutrients for yield and soil quality improvement [117,141,143,145]. As stated before, organic wastes have many mineral nutrients [164]. These are present in quantities and a variety that depend on the origin of the waste, whether it has been subjected to some type of stabilizing treatment; agricultural and livestock practices like fertilization, pesticide treatments, and the application of medicines; or soil and environmental pollution, among other activities. This has given rise to new proposals for the use of waste, such as the recovery of bioactive substances for the pharmaceutical and cosmetics industry, energy generation, animal feeding, and the production of materials for water purification, construction, or technosols [25,135–137,165]. Organic waste incorporated into the soil as an amendment or a growth substrate also is a rich source of nutrients. However, it is not known exactly which, how much, when, and how (in the bioavailable or non-bioavailable form) they will be released to be absorbed by plants [166]. This makes its use difficult, as the farmer needs to synchronize the nutritional needs curve of the crop with the nutrient release curve [108].

Previous studies have shown that the release of nutrients from organic residues also depends on other factors such as the previous state of the soil where it is applied, the climatic conditions, and the system for incorporating the residue, among others [108,117,166]. In any case, nutrients become available as microorganisms decompose organic matter. In addition, a rapid release of highly soluble nutrients can occur in phases prior to decomposition [114,167]. Therefore, when a rapid supply of nutrients is required, the presence of a rapidly soluble fraction in the waste is desirable. In the case of pruning residues, date palm leaf prunings show high concentrations of soluble nutrients with high solubility indices (73% Na, 56% K, 63% Ca, 74% Mg, 2% Fe, 66% Mn, 21% Cu, and 67% Zn) in the residues studied by Rodríguez-Espinosa et al. [114,115]. However, in the case of sewage sludge compost, despite its high nutrient concentration in the elemental composition, the soluble fraction is very low, with low nutrient solubility indices (53% Na, 32% K, 1% Ca, 3% Mg, 0% Fem 0% Mn, 1% Cu, and 2% Zn). Therefore, its application seems more suitable for long-term nutrient supply. The nutrient solubility is also important when we want to avoid the consequences of trace element presence in waste [115].

The bioavailability of nutrients is a crucial aspect for crops and plants and is highly variable. The availability of nutrients from manure depends mainly on the type of animal species from which it originates, the livestock breeding system (intensive or extensive), and the season when is applied [159,168,169]. In animal manure, the water-soluble and exchangeable fraction is 2–9.5%, 0.7–6.9%, and 1.4–22.1% for Zn, Cu, and Mo, respectively [159]. Based on the results obtained by Ramos et al. [159], cattle manure coming from an extensive production system showed a lower water-soluble and exchangeable fraction than that from intensive production, generally for the nutrients studied. In wastewater, the bioavailability of phosphorous can vary between 3.4 and 81% [170]. The available P fraction in wastewater sewage sludge was 13%, in fish sludge was 7–26%, and in dried fish sludge was only 4% [171].

However, as stated before, organic waste can entail hidden risks, related to heavy metals, microorganisms, and emerging contaminant contents [36,115]. Therefore, its safety must be ensured prior to application.

### *3.7. Strategies to Improve Mineral Nutrition (Soil, Plant, and Human) and Reduce Hidden Hunger*

Reducing the incidence of hidden hunger is of interest to ensure nutrition security [5,41]. As has been detailed throughout the paper, it is a complex process, and several lines of action are proposed.

In general, a diet poor in micronutrients is the main cause of malnutrition [172]. Therefore, it is important to educate people on eating habits that enhance nutrient-rich and diverse diets. It is important to focus on learning which foods and which parts of them have the required micronutrients in the proper amounts and forms that are more bioavailable for the human body and on communicating how to manage and process them to avoid nutrient loss [55,60]. Samtiya et al. [173] highlighted food fermentation as a processing and preservation technique that can increase the bioavailability of nutrients by up to 30% for Ca, P, Fe, Mn, and Zn in wheat. Other actions are to supply nutrients while cooking or processing the food, as well as the use of supplements [172]. In addition, it should be taken into consideration that the presence of anti-nutrients in ingested foods can affect the ability of the digestive system to absorb and use nutrients [53,61,174].

Human nutrition depends first on fertile soils and crops that absorb nutrients efficiently. In terms of enhancing the efficient use of nutrients, an excellent strategy is to implement sustainable soil management practices that prioritize fertility. The FAO [36] considered that integrated soil fertility management can improve crop yields, while preserving sustainable and long-term soil fertility through the combined judicious use of fertilizers, recycled organic resources, responsive crop varieties, and adequate agronomic practices. As mentioned above, an optimal adjustment of the plant's nutritional needs with the supply of fertilizers and organic matter can also avoid problems of the excess and loss of nutrients. This requires further research mainly due to the wide variety of crop species, cropping systems, climatic conditions, and the types of organic residues and their treatments and application methodologies. Regarding the application of organic residues as a nutritional source, there is increasing interest in the development of technosols using available organic residues [25,165]. Technosols made by residues can provide long-term nutrients in large quantities, as well as rapidly soluble nutrients [111,114,115]. Also, designing and constructing a substrate to facilitate the absorption of nutrients in waste and reduce fertilizer application is a promising method to enhance the circular economy.

In addition, ensuring the sustainability, protection, and restoration of soils and ecosystems is an investment in our nutritional health. This can be achieved by reducing food waste and adopting nature-based solutions [14,36] and also using microorganisms, plants, and other species to reduce pollutant concentrations and immobilize or enhance nutrient cycles and bioavailability. Some strategies combine aquatic with terrestrial farm production, phytoremediation, mycoremediation, bacterioremediation, and biofertilizers [36,52,175–178]. Further, the combination of crops can improve environmental conditions as well as nutrient availability. Zuo and Zhang [179] concluded that intercropping systems could prevent or mitigate Fe deficiency in Fe-inefficient plants.

All of these agronomic strategies and the genetic modification of species contribute to the biofortification of crops [52], which is defined as the enrichment of food or feed crops with at least one mineral or vitamin during cultivation [172]. Furthermore, for the biofortification strategy to have a positive impact on human nutrition, the added nutrients must accumulate and be bioavailable [55,61,180]. Because there are globally consumed foods that are the main supply of nutrients for many diets, it would be appropriate to focus biofortification efforts on the crop sources of those foods. For instance, in 2021, cereals and their products were the main global iron, zinc, magnesium, and phosphorus nutritional supply [181].

Another key aspect is to know the nutritional status of the soil and plants at all times in order to provide the right amount of fertilizer or organic matter [78,149]. Thus, nutritional monitoring techniques and efficient nutrient addition to the soil can be of great interest [36]. Also important is to increase knowledge about local and global soil nutrient depletion and about nutrients and their mobility in organic wastes. Finally, local production must be supported, as nutritional needs must also be addressed locally.

## 4. Conclusions

Previously, food security was looked at through a prism of the ability to access food, but nowadays, the nutritional aspect of the food eaten is also considered important. Therefore, not only must it be ensured that all people have access to food, but also that the food they eat contains the nutrients necessary to remain healthy.

At present, there is still a lot of food loss, with the consequent loss of the nutrients they contain. These nutrients can be reintroduced into biological cycles by using the residues to improve soil quality and nutrient availability, and moreover, to build soils (technosols). Technosols are viable for growing crops and can be designed according to the nutritional needs of soils, crops, and humans. Further, soils must have an adequate mineral content for plant and human nutrition, but most agricultural soils worldwide show mineral deficits. Technosol construction could be a new option for the problem of hidden hunger due to micronutrient deficiency, parallel to improving crop soils with the proper use of waste. But this is a complex task due to the interconnection between soil, crop, and human nutrition.

To decrease hidden hunger, several strategies are required at the agronomic level, in the field of knowledge increase and dissemination, to better understand the functioning of the soil–plant system, and in the area of social education.

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