RESEARCH PAPER

Microgreens as a Sustainable Dietary Strategy to Reduce Iron-Deficiency Anaemia and Support Adolescent Health

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Abstract

Iron deficiency anaemia (IDA) continues to be one of the major micronutrient deficiencies globally, affecting 1.92 billion individuals. Adolescent females are especially susceptible to it owing to their rapid growth and the onset of menstruation. While oral iron supplementation remains the gold standard and first-line treatment for IDA, the results achieved through this approach are marred by adverse effects, poor compliance, and lack of sustainability. Microgreens, on the other hand, have been proposed as a potential food-based solution. Microgreens can be harvested 7 to 21 days after germination and contain bioavailable vitamin C, carotenoids, sulforaphane, flavonoids, folic acid, and iron, which may improve non-haem iron bioavailability and erythropoiesis. The purpose of this review is to analyse how microgreens can serve as a feasible, culturally appropriate, cost-effective, and environmentally friendly solution to adolescent health problems. Special emphasis is put on potential delivery mechanisms such as functional beverages, snacks, and nutraceutical powders. The benefits regarding neuroprotection and psychological well-being, relevance to SDGs 2, 3, 12, and 13, and potential research gaps are also included. Gap in current knowledge include a lack of randomised controlled studies, challenges with regard to the scalability of the intervention in the developing world where IDA is common, and socio-economic barriers. Consequently, incorporating microgreens into adolescent diet programs provides an evidence-based, holistic way to align public health, adolescent mental health, and sustainable food system innovations.

Keywords: microgreens; iron-deficiency anaemia; adolescent nutrition; mental health; cognitive function; neuroprotection; non-haem iron bioavailability; sustainable dietary interventions; functional foods; urban farming, sustainable development goals, LMICs

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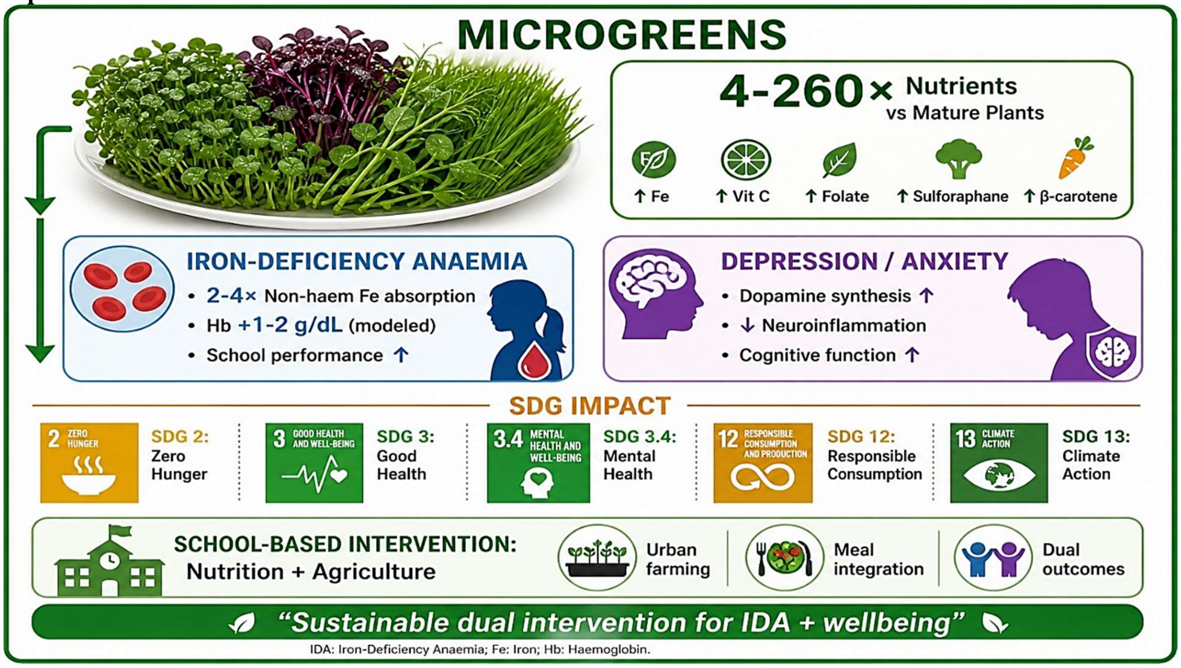
Graphic Abstract



1. Introduction

The continued existence of anaemia as a major public health issue on a global scale indicates a noticeable disconnect between current interventions and the physiological and socio-economic challenges involved. Approximately 1.92 billion people suffered from

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anaemia globally in 2021, an increase from 1.5 billion cases recorded 30 years prior (GBD 2021 Anaemia Collaborators, 2023). Globally, anaemia is considered a health problem that disproportionately impacts females within the age range of 15 to 49 years, maintaining a stagnant prevalence rate of 30.7%, which equates to more than 500 million women (World Health Organization, 2025).

The group that is most vulnerable to anaemia includes young females who are aged 10-19 years. This vulnerability is even more evident in developing nations, with estimated prevalence figures ranging between 45% and 60% (Anwar et al., 2025). The impact of IDA during adolescence encompasses many adverse effects across the lifespan, including decreased cognition, diminished immune function, reduced physical capacity, impaired growth, and adverse pregnancy outcomes (Biswas et al., 2025; Tesfaye et al., 2015).

Although oral iron supplementation and food fortification are the two main interventions that provide measurable immediate benefits, they are undermined by adverse effects such as abdominal discomfort, supply chain disruptions, inadequate regulatory oversight, and poor adherence to treatment, and pervasive socio-economic inequalities (Ge et al., 2025). Given the persistent challenges mentioned, a fresh perspective centred on sustainable, culturally acceptable, food-based strategies is urgently required. Utilizing locally grown, nutrient-dense crops offers a sustainable and culturally acceptable pathway to providing populations with the essential micro- and macronutrients. Functional foods of plant origin possess compounds of great importance for their role in disease prevention and health promotion, including flavonoids, phenolics, anthocyanins, tannins, alkaloids, and other antioxidants (Ullagaddi, 2025).

Microgreens, the young seedlings of vegetables, herbs, grains, and legumes harvested when the first true-leaves appear, approximately 7 to 21 days after germination, have emerged as a viable source of nutrient-rich food that can be grown and consumed by at-risk populations facing "hidden hunger" (Bhaswant et al., 2023; Moinuddin et al., 2025). Research indicates that microgreens possess significantly higher nutrient densities than mature vegetables, with concentrations of vitamins, minerals, and polyphenols typically ranging from 4 to 40 times greater than their mature equivalents (Bhaswant et al., 2023; Kyriacou et al., 2016; Xiao et al., 2012). Critically, several microgreen species are rich in both non-haem iron and their principal dietary enhancers for absorption; vitamin C (ascorbic acid) and carotenoids (Xiao et al., 2012). Therefore, the delivery of iron using microgreens does not rely on any external enhancers and instead creates a single bioavailable source of iron. As fresh, nutrient-dense plant produce, microgreens are generally well-tolerated with no risks of overdose or side effects. Thus, they offer a natural, holistic, and highly bioavailable form of the mineral. This integrated delivery system ensures superior nutrient assimilation while overcoming the common challenges associated with conventional iron supplementation approaches, ultimately enhancing adherence rates.

Consuming microgreens presents an array of potential health benefits, along with a connection to sustainable nutrition. Grown indoors or in small soil trays, they use significantly fewer resources than traditional field agriculture, consuming up to 95% less land and water (Benke & Tomkins, 2017). By including microgreens in the diets of adolescents, it is possible to address the burden of IDA while simultaneously supporting the Sustainable Development Goals (SDGs) 2 (Zero Hunger), 3 (Good Health and Well-being), 12 (Responsible Consumption and Production), and 13 (Climate Action).

The scope of this narrative literature review includes the following topics: (i) the epidemiology and pathophysiology of iron-deficiency anaemia in adolescents; (ii) the nutritional and phytochemical characteristics of microgreens in relation to iron status and erythropoiesis; (iii) mechanisms responsible for enhanced bioavailability of non-haem iron from microgreen compounds; (iv) the contribution of microgreens to neurocognitive and mental health outcomes; (v) the influence of traditional food processing and meal-level optimisation strategies on iron absorption; (vi) practical dietary delivery systems and product innovations for the adolescent population; (vii) safety, standardisation, and regulatory challenges; (viii) current evidence gaps and priorities for future research; (ix) development of a multi-tier integrated framework for policy implementation linking community cultivation to clinical application; and (x) research governance within sustainable development contexts.

2. Methodology

For this narrative review, searches were executed in the Scopus, PubMed/MEDLINE, and Google Scholar databases using the search terms "adolescent" AND "anaemia" OR "iron deficiency"; "sustainable diet" AND "anaemia" OR "iron deficiency"; "functional food" AND "microgreens". Additional searches related to adolescent girls, mental health and well-being, microgreen processing technology, microgreen urban farming economics and SDGs were conducted using same keywords. The search was restricted to peer-reviewed literature published exclusively in English language. Exclusion criteria comprised studies focusing on hereditary hemoglobinopathies such as sickle cell anaemia, and studies which covered broader demographics of all women of reproductive age without adolescent-specific stratified data.

3. Iron-Deficiency Anaemia in Adolescent Girls: Epidemiology and Pathophysiology

3.1. Global Burden and Adolescent Vulnerability

In 2021, the Disability-Adjusted Life Years (DALYs) attributable to IDA amounted to 52 million across the world, with the majority occurring in South Asia and sub-Saharan Africa (Luo et al., 2025). Adolescent females aged between 10 and 19 years need an intake of 15 milligrams of iron daily to satisfy physiological requirements. The recommended intake accounts for rapid growth during this age stage (approximately 0.7mg/day) and menstrual losses (approximately 0.5 to 1.0 mg/day), while factoring in a typical dietary iron absorption rate of 10% (Beard, 2000). This requirement is difficult to achieve particularly in Low- and Middle-Income Countries (LMICs), due to low dietary diversity and diets mostly comprised of non-haem iron which has an even lower absorption rate compared to haem iron (Safiri et al., 2025; Soni et al., 2025).

The overall demand for iron resulting from physiological growth, combined with social determinants (Thomas et al., 2015), creates heightened nutritional risk. Residing in a rural area, low socioeconomic status, food insecurity, and peer-influenced dietary patterns that encourage processed and convenience foods, along with low nutritional literacy together amplify vulnerability to IDA (Gore et al., 2024; Jha et al., 2025; Sari et al., 2022; Wati et al., 2023). All of these factors contribute to the increased risk of IDA. The presence of early menarche (age at first menstruation) and being underweight also increase the risk of developing IDA (Kavthekar et al., 2016; Wirth et al., 2025), thus IDA is a condition with multiple causative factors and cannot be solely addressed with interventions that focus on a single nutrient (Soni et al., 2025).

3.2. Consequences of IDA During Adolescence

The consequences of IDA during this critical developmental window are multi-systemic (Figure 1). Cognitively, iron is required for producing dopaminergic neurotransmitters, promoting myelination, and maintaining the normal functioning of the hippocampus (Georgieff, 2011). Consequently, if a deficiency occurs during adolescence, there may be long-term deficits in attention, learning, and academic performance that are unlikely to be completely reversed by late treatment (Clark, 2009; McCann & Ames, 2007). Immunologically, iron is necessary to support lymphocyte growth and natural killer cell cytotoxic activity (Ni et al., 2022); thus, the presence of IDA negatively impacts both innate and adaptive immunity (Ni et al., 2022; Preston et al., 2021; Schimmer et al., 2025). In addition, from a reproductive health viewpoint, adolescent females who conceive while having inadequate iron stores face a greatly increased risk of maternal anaemia, preterm delivery, intrauterine growth restriction, and neonatal death (Obeagu & Obeagu, 2025).

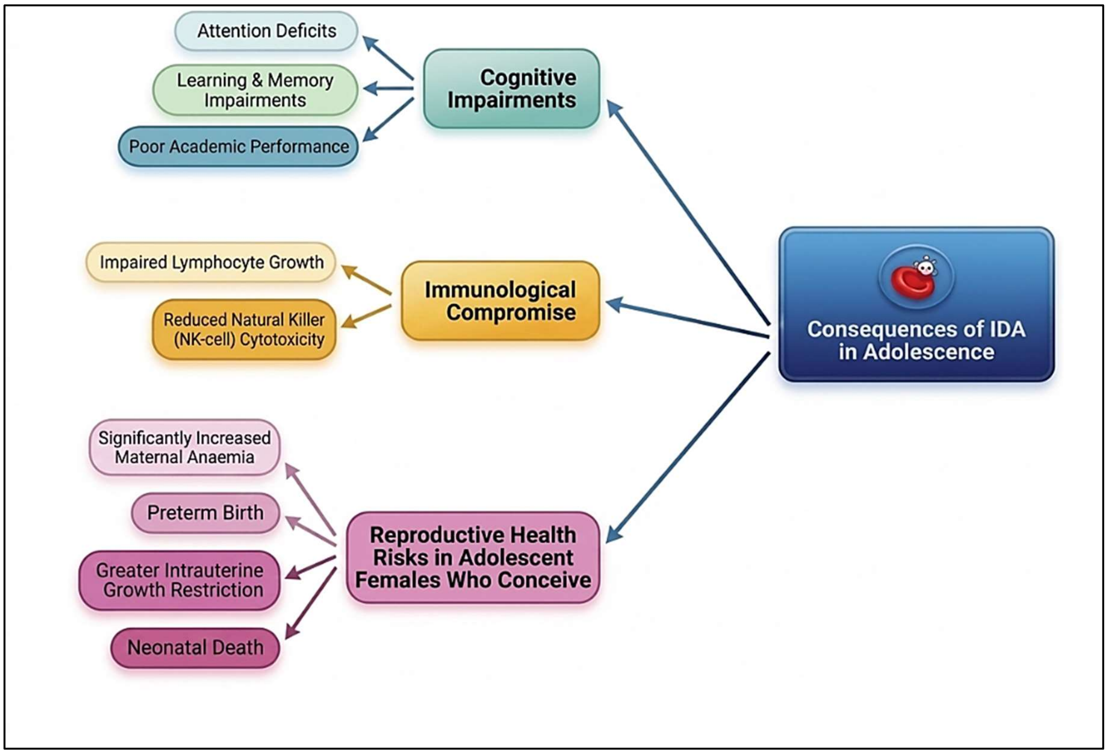


Figure 1. Consequences of Iron-Deficiency Anaemia in Adolescence

3.3. Role of Micronutrient Synergies: Iron, Folate and Vitamin B_{12}

Nutritional anaemia is common in adolescents due to poor diet, with IDA being the most prevalent form. However, a lack of folate and vitamin B_{12} in adolescents can also cause anaemia by disrupting erythropoiesis (red blood cell production). For instance, folic acid plays an important role in the synthesis of 5,10-methylene-tetrahydrofolate, which donates a one-carbon group for deoxythymidine monophosphate (dTMP) production. This process promotes DNA synthesis during the formation of red blood cells (Koury & Ponka, 2004). As a result, megaloblastic anaemia may develop, characterized by macrocytic red blood cells that impair oxygen transport and lead to systemic hypoxia (Castellanos-Sinco et al., 2015). Concurrently, vitamin B_{12} deficiency prevents the conversion of 5-methyltetrahydrofolate back into active tetrahydrofolate, a phenomenon known as the "methyl-folate trap" (Hoffbrand & Jackson, 1993). While this functional folate deficiency similarly results in megaloblastic anaemia, it is uniquely associated with neurological symptoms (Green, 2017; Raynolds, 2006). The major clinical challenge created by the duality of iron and folate deficiencies is that they are frequently found together in people consuming plant-based diets (Akinwumi et al., 2025). This co-existence of dual deficiencies can generate a mixed population of microcytic and macrocytic red blood cells, making the clinical diagnosis challenging. This reinforces the need for dietary interventions that address multiple micronutrient deficiencies simultaneously (Chan et al., 2007; Socha et al., 2020).

3.4. Microgreens, IDA Correction, and Adolescent Mental Health

IDA in adolescence is linked to emotional symptoms, such as depression, anxiety, and cognitive deficits, due to altered dopamine and serotonin production, impaired myelination, and disruption of iron-dependent enzymes necessary for proper neuron function. Consequently, youth with IDA will exhibit a 2- to 3-fold increase in the prevalence and severity of these psychological symptoms (Chen et al., 2013; Grantham-McGregor & Ani, 2001). Specifically, the folate and B-complex vitamins contained in pes and wheatgrass microgreens help sustain one-carbon metabolism and homocysteine remethylation pathways, which are crucial for neurotransmitter synthesis and genome stability during the rapid proliferating and maturation of neurons (Young, 2007). Furthermore, sulforaphane (SFN) and polyphenols found in broccoli and red cabbage microgreens induce nuclear factor erythroid 2-related factor 2 (Nrf2)-mediated signalling, thus leading to decreased neuroinflammation and oxidation (Houghton et al., 2016; Scapagnini et al., 2011; Sun et al., 2017). As neuroinflammation and oxidative stress are related to mood disorders and depression in adolescents (Zhao et al., 2026), it can be deduced that these pathways may have some therapeutic importance. Crucially, dietary nitrates present in beet and arugula microgreens facilitate cerebrovascular perfusion, thereby promoting executive function and attention (Vaccaro et al., 2024). By leveraging this high nutrient density profile (Seth, et al., 2025), a targeted dietary strategy of eating 50g/day of vitamin C- and iron-rich microgreens can alleviate the cognitive symptoms associated with IDA and elevate the overall well-being of youth (Seth et al., 2025). This positions microgreens as a synergistic dietary intervention for improving haematological and mental health outcomes in vulnerable adolescent populations, directly contributing to SDG 3.4.

4. Dietary Iron Bioavailability: Mechanisms and Modulators

4.1. Haem Versus Non-Haem Iron

Iron in the diet exists in two different forms, with two distinct efficiencies for absorption (Figure 2). The first, known as haem iron, is derived from haemoglobin and myoglobin found in animal sources and is absorbed (20-30% efficiently) via a receptor-mediated pathway that operates independently of dietary composition and luminal pH (Piskin et al., 2022). However, the absorption of non-haem iron that comes from plant-based foods, legumes, and fortified foods occurs less efficiently (estimated at 1–10%), because it is susceptible to dietary inhibitors and luminal factors (Malik et al., 2025; Piskin et al., 2022).

To be transported through the apical membrane of intestinal cells, non-haem iron must first be reduced from ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}) by the brush-border enzyme duodenal cytochrome b (Dcytb) and dietary ascorbic acid (Catapano et al., 2025; Ganasen et al., 2018). Once reduced, Fe^{2+} is transported into the cell via Divalent Metal Transporter 1 (DMT-1). Ferroportin then transports iron into the portal circulation from the basal membrane, with this process being regulated by the hepatic hormone hepcidin (Knutson, 2017; Przybyszewska & Zekanowska, 2014). The understanding of this process is important in order to design dietary strategies to maximise net iron absorption.

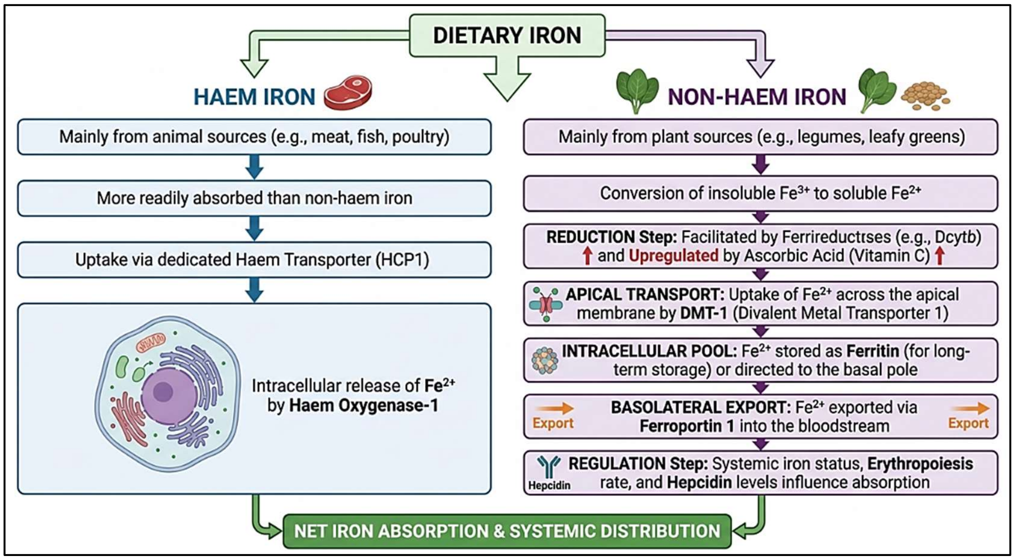


Figure 2. Iron Absorption Mechanisms

4.2. Dietary Enhancers and Inhibitors

Table 1 provides a summary of some the major dietary modifiers that influence non-haem iron bioavailability, along with food sources for each item. The most potent known enhancer of non-haem iron absorption is ascorbic acid (vitamin C), which acts by reducing Fe^{3+} to Fe^{2+} and chelating with the iron to form a soluble iron-ascorbate complex that maintains its solubility even in the presence of phytates and polyphenols (Lynch & Cook, 1980). This enhancing effect is concentration-dependent and requires that ascorbic acid and non-haem iron be consumed simultaneously within the same meal (Piskin et al., 2022).

Table 1. Key Dietary Enhancers and Inhibitors of Non-Haem Iron Absorption

Enhancers of Non-Haem Iron Absorption	Food Sources	Mechanism
Vitamin C (Ascorbic Acid)	Citrus fruits, tomatoes, bell peppers, amla, broccoli microgreens	Reduces $Fe^{3+} \rightarrow Fe^{2+}$; forms soluble chelate resisting phytate inhibition
Carotenoids (β-carotene)	Carrots, sweet potatoes, red cabbage & cilantro microgreens	Overcomes phytate/polyphenol blocks; keeps iron soluble in the lumen
Organic Acids (citric, malic, lactic)	Citrus fruits, apples, berries, fermented foods (lactic acid)	Chelates iron and lowers luminal pH, preventing precipitation
Animal Protein (MFP factor)	Meat, poultry, fish, seafood	Cysteine peptides bind non-haem iron to maintain solubility
Sulforaphane (SFN)	Broccoli, radish microgreens, other cruciferous vegetables	Activates Nrf2 pathway; antioxidant action may protect absorptive enterocytes
Inhibitors	**Food Sources**	**Mechanism**
Phytic Acid (Phytate)	Whole grains, legumes, nuts, seeds	Strongly chelates iron into highly insoluble complexes
Polyphenols/Tannins	Tea, coffee, red wine, sorghum	Binds and precipitates iron within the intestinal lumen
Calcium	Dairy products, milk, cheese	Acts as a noncompetitive inhibitor affecting apical uptake
Oxalic Acid	Spinach, rhubarb, chard	Binds iron to form insoluble iron oxalate crystals

Sources: García-Casal et al., 1998; Harada et al., 2011; Lynch & Cook, 1980; Salgado et al., 2023; Piskin et al., (2022).

Provitamin A carotenoids such as β-carotene and α-carotene, represent another class of effective enhancers of non-haem iron absorption. According to a study by García-Casal et al. (1998), the addition of β-carotene to meals containing rice as the sole non-haem iron source increased iron absorption more than threefold. When combined with corn- or wheat-based meals, it increased iron absorption nearly twofold (1.8-fold). Although the exact molecular pathways remain unknown, the primary accepted mechanism involves carotenoids forming a stable complex with iron in the intestinal lumen. This complex maintains iron solubility at an intestinal pH of 6.0, effectively preventing polymerization and shielding the mineral from the inhibitory effects of dietary phytate and polyphenols. Utilizing these carotenoid-rich enhancers is especially important for populations who rely primarily on cereal grains as their staple food, as these same demographics face the greatest risk for developing IDA.

There are many factors present in plant-based diets that make it difficult for the body to absorb non-heme iron. Phytic acid (inositol hexaphosphate) is one of these factors, constituting 1-5% of the dry weight of whole grains, legumes, and seeds (Bohn et al., 2008; Graf & Eaton, 1990). The phytic acid present in food forms insoluble compounds with iron in the digestive tract which cannot be broken down by the endogenous digestive enzymes (Gupta et al., 2015; Kumar et al., 2010). Even if the phytic acid concentration in a meal is as low as 10 mg, it can reduce the absorption of non-haem iron by 50% (Hurrell & Egli, 2010).

Similarly, polyphenolic compounds, such as tannins from tea and coffee, as well as flavonoids from many vegetables, are other examples of compounds that significantly decrease the absorption of non-haem iron by 30 – 50 % when co-ingested (Delimont et al., 2017; Lesjak et al., 2019; Piskin et al., 2022). Rather than competing as a transport substrate inside the DMT-1 pathway, calcium operates as a non-competitive inhibitor, decreasing apical DMT-1 membrane expression and destabilizing the transport process (Thompson et al., 2010). Elucidating these distinct inhibitory pathways is crucial for developing meal-level optimisation strategies that bypass mineral precipitation and transport blockades.

4.3. Traditional Food Processing as a Bioavailability Strategy

Using traditional cooking techniques offers an evidence-based, low-cost approach to mitigating dietary inhibitors and enhancing non-haem iron bioavailability. Soaking and germinating grains and legumes effectively activates endogenous phytases, which hydrolyse phytic acid into lower inositol phosphates, thereby improving mineral accessibility (Gupta et al., 2015). For instance, germinating finger millet and wheat can degrade phytic acid concentrations by 30-60% (Patel & Dutta, 2018). Concurrently, microbial fermentation generates organic acids, such as lactic acid, which lower the luminal pH and stimulate native phytase to further break down phytic acid (Debbarma et al., 2026). Beyond biological processing, preparing meals in cast-iron cookware provides a passive method for increasing dietary iron density. Foods cooked using cast-iron pots and pans exhibit a substantial increase in elemental iron content compared to foods cooked using other cookware materials. This observation is especially relevant for resource-limited communities that rely predominantly on plant-based staples (Alves et al., 2019; Sharma et al., 2021).

5. Microgreens: Nutritional Profile and Relevance to Iron Status

5.1. Definition, Classification, and Distinction from Sprouts

Microgreens, which are seedlings of tender young vegetables, herbs, cereals, legumes and edible flowers, are grown for 7-21 days from the time the cotyledon (seed leaf) is fully developed and true leaves begin to appear. The height of microgreens will generally range from 2.5 to 7.5cm. There are also notable differences between sprouts and microgreens beyond just growing height. Sprouts are grown indoors in a water medium and are not exposed to light or soil. Microgreens are grown on a medium (such as soil or soilless mat) as opposed to in water (sprout). Their roots develop under the soil while their leaves grow above ground and are harvested by cutting and everything except for roots are consumed in microgreens. Microgreens often contain higher levels of specific phytochemicals, such as carotenoids and chlorophyll because they undergo active photosynthesis and grow for a longer period in a nutrient-rich medium compared to sprouts (Wojdyło et al., 2020).

While many plant families can produce microgreens, research has primarily focused on the *Brassicaceae* family (such as broccoli, radish, kale, arugula, mustard, and red cabbage) since they contain a significant amount of glucosinolates, the precursors required to generate bioactive SFN, relative to other types (Guardiola-Márquez et al., 2023). Other plant microgreen families include *Amaranthaceae* (such as amaranth, beets, Swiss chard and spinach) which are all good sources of iron, calcium and carotenoids (Chandel et al., 2026); *Fabaceae* (such as peas, lentils, mung and chickpeas) that are excellent sources of folate, vitamin C and protein (Gupta et al., 2023); and *Poaceae* (cereal microgreens like barley and wheat grass) which contain high levels of chlorophyll, iron and B-vitamins (Niroula et al., 2019).

5.2. Nutritional Superiority Over Mature Counterparts

Microgreens are often cited and well documented as having superior nutritional value compared to their full-sized counterparts. Xiao et al. (2012) analysed 25 varieties of commercially available microgreens, and found that every microgreen was nutritionally superior in at least one selected nutrient when compared with its mature equivalent as shown in Table 2.

Table 2. Comparative Bioactive Content of Selected Microgreens versus Mature Vegetables

Microgreens Species	Bioactive Compound	Microgreens (per 100g FW)	Mature Plant (per 100g FW)	Fold Diff.
Broccoli	Vitamin C	80–120 mg	45–60 mg	~2×
Red Cabbage	Vitamin C	147 mg	24.4 mg	~6×
Red Cabbage	Vitamin E	24.1 mg	0.6 mg	~40×
Red Cabbage	β-carotene	11.5 mg	0.044 mg	~260×
Cilantro	Lutein/Zeaxanthin	10.1 mg	0.9 mg	~11×
Radish	Vitamin E	87.4 mg	1.5 mg	~58×
Amaranth	Iron	3.9 mg	1.8 mg	~2.1×
Sunflower	Vitamin E	1.3 mg	0.3 mg	~4.3×

FW = fresh weight. Sources: Bhaswant et al. (2023); Partap et al. (2023); Xiao et al. (2012).

Vitamin C concentration levels are remarkably high in both broccoli (80-120 mg/100 g of fresh weight (FW)) and red cabbage microgreens (147 mg/100 g FW) (Xiao et al., 2012). Therefore, a serving size of 50 g of red cabbage microgreens will yield 73.5 mg of ascorbic acid, which is enough to significantly increase the absorption of non-haem iron. In addition, red cabbage microgreens contain 11.5 mg of β-carotene/100 g FW, which is 260 times greater than mature red cabbage, making them an excellent source of both provitamin A carotenoids and enhancers of iron absorption from non-haem sources.

5.3. Microgreens and Erythropoiesis-Relevant Micronutrients

Beyond supplying vital vitamins and minerals such as ascorbic acid, carotenoids, and magnesium, microgreens serve as exceptional sources of diverse nutrients that directly contribute to blood cell formation (erythropoiesis). Table 3 details many of the microgreen species considered in relation to iron status and the production of red blood cells.

For instance, pea microgreens are a vital source of folate (The Mighty Microgreen, n.d.), which supports nucleotide synthesis in rapidly dividing cells during the germination phase of the plant; it is also important for the development of erythroid precursors in the human bone marrow (Maynard et al., 2024). While less documented than the *Brassicaceae* family, wheatgrass (*Triticum aestivum*) microgreens provide a significant amount of chlorophyll. This pigment is structurally analogous to haemoglobin, differing only by the presence of a central magnesium atom rather than an iron atom. Furthermore, wheatgrass yields adequate quantities of magnesium and zinc, the latter functions as the mandatory zinc cofactors for the carbonic anhydrases enzymes within mature red blood cells, while concurrently bolstering the immune pathways typically impaired by severe IDA (Gunjal et al., 2024).

Table 3. Microgreens Species and Their Specific Relevance to Iron Status and Erythropoiesis

Microgreens Species	Key Bioactive Compounds	Relevance to Iron Status & Erythropoiesis	Additional Nutritional Notes
Broccoli	Sulforaphane, Vitamin C, Folate	Intestinal antioxidant protection; supplies critical B9 for erythroblast cell line development	Anti-inflammatory; protects gut epithelium to support optimal non-haem iron absorption
Red Cabbage	Vitamin C, Vitamin E, Anthocyanins	Promotes apical ferric reduction ($Fe^{3+} \rightarrow Fe^{2+}$); mitigates tissue oxidative stress	Minimizes systemic oxidative stress markers within iron-deficient cell lines
Amaranth	Iron, Calcium, Vitamin C, Vitamin K	Direct cellular mineral replenishment; supplies bioavailable elemental iron	High raw Vitamin C content acts as a built-in counter-mechanism to native oxalates
Radish	Vitamin C, Vitamin E, Folate	Enhances non-haem transport; B9 supports active erythroblast division	Highly dense tocopherol fractions help stabilize red blood cell lipid membranes
Cilantro	β-carotene, Lutein, Vitamin C	Prevents phytate/polyphenol precipitation blocks in the gut lumen	Upregulates systemic Vitamin A status, supporting overall transferrin iron delivery
Sunflower	Vitamin E, Vitamin B_6, Zinc	Promotes metabolic energy; B_6 acts as an essential cofactor for haem synthesis	Highly palatable, nutty profile; easily consumed in raw portions by adolescents

Pea	Folate, Vitamin C, Iron	Essential for erythrocyte DNA synthesis; megaloblastic anaemia prevention	High folate density supports erythropoiesis
Wheatgrass	Iron, Zinc, Vitamin C, Amino Acids	Synergistic non-haem mineral absorption; cellular mineral replenishment	Highly bioaccessible when freshly juiced, eliminating fibrous cell-wall breakdown barriers

Sources: Bhaswant et al. (2023); Gunjal et al. (2024); Partap et al. (2023); Xiao et al. (2012)

5.4. Sulforaphane and the Nrf2 Pathway: Indirect Benefits for Iron Status

SFN derived from the *Brassicaceae* family, influences systematic iron status through downstream biochemical pathways rather than via direct dietary mineral contribution. While SFN exhibits minimal immediate nutritional value, it primarily regulates iron homeostasis indirectly by modulating cellular responses to oxidative stress (Elvandari et al., 2024). This process begins when glucoraphanin is hydrolyzed by the endogenous enzyme myrosinase during mastication and digestion of cruciferous microgreens (Bouranis et al., 2023). This enzymatic cleavage releases bioactive SFN, which then subsequently activates cytoprotective cascades that manage iron-mediated reactive oxygen species (ROS) and support systemic mineral preservation.

For instance, SFN stabilizes the Nrf2 pathway, partially by modulating cellular ROS dynamics (Houghton et al., 2016). This pathway drives up the upregulation of ferritin (an iron-storage protein), haem oxygenase-1 (HO-1), and various native antioxidant enzymes. Collectively, these protective molecules shield erythrocyte membranes from oxidative damage and prevent oxidative haemolysis, a key pathological mechanism of anaemia prevalent during chronic or acute inflammation (Ruhee & Suzuki, 2020).

In addition, downstream inflammatory networks such as the Nuclear Factor kappa-light-chain-enhancer of activated B cells (NF-kB) pathway, alter systemic iron status by up-regulating pro-inflammatory cytokines including Interleukin-6 (IL-6) and Tumour Necrosis Factor-alpha (TNF-α) (Ghio & Weinberg, 2012). SFN-mediated suppression of the NF-kB cascade down-regulates IL-6 and TNF-α expression, leading to a decreased production of hepcidin, the primary hormonal regulator of iron homeostasis (Nemeth et al., 2003). Minimising circulating hepcidin allows for the unimpeded export of elemental iron into the portal circulation via enterocyte and macrophage basolateral ferroportin channels. Consequently, sulphur-rich broccoli microgreens stand out as a highly effective food source of bioavailable SFN, providing a potent dietary intervention strategy to mitigate systemic risk factors for IDA (Bouranis et al., 2023).

6. Dietary Delivery Formats for Adolescent Populations

6.1. Fresh Microgreens in Meal Integration

Microgreens will likely increase adolescent consumption of foods in general, as well as contribute

Microgreens will likely increase adolescent consumption of foods in general, as well as contribute to greater amounts of iron-rich meals. Examples of culturally relevant usage for microgreens would be to add broccoli or amaranth microgreens to traditional South Asian *dals* (lentils), chutneys, or *parathas*. Similarly, radish or pea microgreens can be added to *chaats* (popular savoury street snacks) and salads topped with lemon dressing. For beverage-based delivery, wheatgrass or sunflower microgreens can be blended into mango or banana *lassis*, while fresh microgreens can serve as functional garnishes for *idlis* or *dosas* paired with tomato-based *sambar*, which is also rich in vitamin C. For many countries in sub-Saharan Africa, microgreens can be easily incorporated into stews, served with *ugali* (a dense, staple maize porridge), or included in the dish along with moringa leaves (another excellent source of iron).

The primary principle that underlies all these uses of microgreens is meal-level optimisation (see Figure 3). This approach requires the co-ingestion of foods that are high in iron (such as lentils, leafy vegetables, and fortified staples) with vitamin C-rich microgreens to maximise bioavailability, while limiting the simultaneous consumption of tea, coffee, and calcium-rich dairy products. A target intake of 30-50 g of vitamin C-rich microgreens can enhance the absorption of non-haem iron by at least twofold (Khoja et al., 2020).

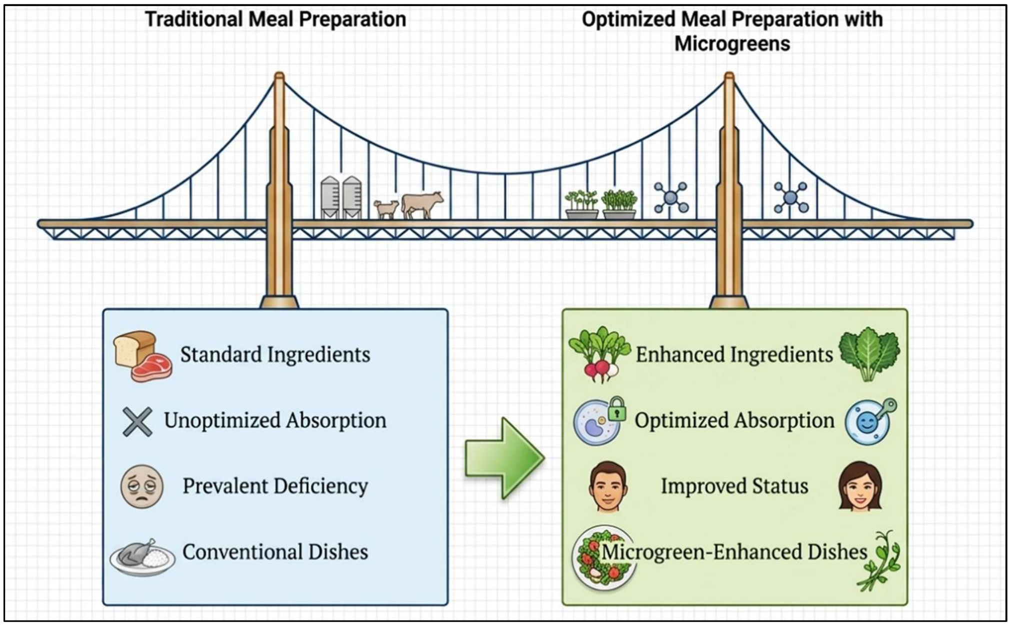


Figure 3. Microgreen Integration for Iron Absorption

6.2. Value-Added Products for Adolescent Acceptability

The primary barrier to fresh microgreen consumption by adolescents is sensory acceptability. The peppery, bitter, or strongly "grassy" flavour profiles of many *Brassicaceae* microgreens may conflict with the dietary preferences of adolescents, particularly those accustomed to flavours of processed foods. Value-added processing offers solutions that simultaneously improve palatability, extend shelf life, and permit the controlled dosing of bioactive compounds.

6.2.1 Functional Beverages

Cold-pressed juices and blended smoothies incorporating microgreens (broccoli, amaranth, and red beet) with sweet fruit bases (such as mango, pineapple, and banana) effectively mask bitter or "grassy" flavour notes. Crucially, this non-thermal approach preserves heat-sensitive vitamins C and E, as well as enzymatic activity, including myrosinase required for glucoraphanin-to-SFN conversion that would otherwise be lost during traditional thermal processing (Belošević et al., 2024). Ready-to-drink microgreen shots, typically 30-60 mL volumes with concentrated microgreen content are gaining traction in health-conscious markets and could be adapted for school nutrition programmes in LMICs as nutrient-dense supplements to standard school meals.

6.2.2 Dehydrated Powders and Snack Fortification

Freeze-drying or lyophilisation has been shown to significantly preserve vitamins, antioxidants, and other bioactive compounds compared to other drying methods (Mu et al., 2025). This technique produces shelf-stable products suitable for enrichment in baked goods, *chapati* flour mixes, energy bars, and breakfast cereals. For example, the substitution of wheat flour with 5% to 15% *Brassicaceae* microgreen powder in breads and crackers has been shown to increase both the total phenolic content and antioxidant capacity significantly, with no observed deterioration in acceptable organoleptic properties (Klopsch et al., 2019). Importantly, the amount of iron, zinc, and magnesium contained within microgreen powders remains highly stable under thermal processing, offering a reliable method to incorporate minerals into fortified, baked products (Jauregui et al., 2025). It is also possible to produce baked products using air convection-dried microgreens at relatively low temperatures (40-50°C), reducing processing costs for LMIC nations; however, this comes at the expense of ascorbic acid losses (15% to 40%) compared to freeze drying (Gunjal et al., 2025).

6.2.3 Nutraceutical Capsules and Supplements

The encapsulation of microgreen extracts or powders can provide a means of obtaining standardised doses of important bioactive ingredients (such as SFN, lutein, and phylloquinone) for targeted clinical supplementation. Nano- and microencapsulation protect unstable components from degradation by gastric acid during gastrointestinal (GI) transit, and enables them to be released specifically in the small intestine where iron is absorbed (Piskin et al., 2022). Currently, the high capital cost of manufacturing microgreen supplements limits their access within most LMICs. However, based on anticipated reductions in manufacturing costs driven by the large-scale implementation of urban vertical farming, it is expected that over the next decade the affordability of these supplements will improve significantly (Singh et al., 2024).

7. Microgreens Within Sustainable Food Systems

7.1. Environmental Sustainability of Microgreens Production

Microgreens, due to their very short growth cycle (7-21 days) and small growing space requirements, are well-suited for sustainable production. In addition, they can be grown using Controlled Environment Agriculture (CEA) technologies (such as vertical farming, hydroponics, and aeroponics), which have made them an increasingly popular option for many businesses (Benke & Tomkins, 2017). Compared to growing vegetables in a traditional field, cultivating microgreens within a controlled environment yields the following benefits: (1) 90-95% less water is used; (2) cultivation can occur at any time of the year because crops are not dependent on the seasons and weather; (3) microgreens can be produced within urban centres, thereby reducing the distance food needs to travel; (4) little or no pesticide is used; and (5) a greater amount of nutrition is produced per square foot than if they were produced in a traditional field (Rajaseger et al., 2023), creating an important advantage for communities throughout South Asia and Africa that face agricultural land scarcity (Gunapala et al., 2025).

Furthermore, on a community-wide scale, microgreen cultivation does not require elaborate and expensive equipment. Instead, it utilises accessible, low-cost resources such as repurposed containers or cardboard trays, coco coir substrate, and natural lighting to produce nutrient-dense microgreens in a 10-14-day cycle. This low-input approach facilitates implementation in diverse settings, including schools and households. Consequently, establishing community-based microgreen programmes offers an effective opportunity to integrate food production with nutritional education, fostering both nutrition knowledge and practical agricultural skills in children.

7.2. Alignment with Sustainable Development Goals

Microgreens can play an important role in strategies for preventing adolescent anaemia, linking them to numerous United Nations Sustainable Development Goals (see Table 4 for the connections between microgreens, anaemia, and these goals).

7.3. Economic Viability and Entrepreneurship Opportunities

The potential economic benefits associated with the introduction of microgreens in nutrition-sensitive strategies are enhanced by the high productivity (in terms of income per area unit) of microgreen cultivation and the rapidly increasing demand for functional and clean-label foods. In a global perspective, the value of the microgreens industry amounted to USD 1.7 billion in 2022 and is expected to reach USD 2.61 billion by 2029, reflecting a CAGR of 11.7% for this time period (Singh et al., 2024). The reason behind such an increase is the rising demand among consumers for health-promoting foods (Lone et al., 2024; Rawat et al., 2024; Seth et al., 2025; Singh et al., 2024). In LMICs, microgreen cultivation in schools may serve as an efficient approach to improve the nutritional status of adolescents alongside fostering entrepreneurshipat the community level. Such programs, when developed through cooperation with local producers, are capable of providing a steady income source for schools and nutritious food products for adolescents.

Table 4. Alignment of Microgreen-Based Anaemia Intervention with UN Sustainable Development Goals

Goal	Title	Relevance to Microgreen-Anaemia Strategy	Practical Example
SDG 2	Zero Hunger	Improving food security and nutrition through affordable microgreen-enriched foods	Iron-fortified snacks, millet-microgreen porridges reaching schools in LMICs
SDG 3	Good Health & Well-being	Reducing anaemia-related morbidity and supporting adolescent growth	Microgreens supplementation of adolescent diets; nutrition education programmes
SDG 12	Responsible Consumption	Reducing food waste via value-added microgreens products; utilising local food systems	Freeze-dried powders from surplus harvests; circular urban farming loops
SDG 13	Climate Action	Lowering carbon footprint through urban vertical farming; reducing food miles	Hydroponic indoor systems powered by renewables; minimal pesticide use

LMICs = Low- and Middle-Income Countries.

7.4. Economic and Logistical Challenges: Contextualising Microgreens Against Nutrient Dense Alternatives

Despite their exceptional nutritional profile, microgreens remain largely inaccessible to the populations most burdened by IDA. The retail price of microgreens is approximately four to ten times higher than their base cultivation cost (Ghoora & Srividya, 2018). Furthermore, the indoor infrastructure required for consistent production (such as climate-controlled environments, specialised growing media, and frequent seed procurement) imposes capital and operational costs that are prohibitive in low-resource settings (Singh et al., 2025). These restrictive costs create an insurmountable barrier to entry, locking smallholders out of the market due to lack of financing, specialised inputs, and technical expertise.

Consequently, while microgreens are highly flexible on domestic scale, commercial-grade vertical systems remain socioeconomically stratified (Gokulakrishnan et al., 2025; Nooriyan & Roosta, 2025). This forces producers to target premium luxury markets to offset high operational overhead making the business model highly vulnerable to local economic shocks.

In contrast, the leaves of *Moringa oleifera* are one of the most well-known functional greens due to their high iron concentration of approximately 28 mg/100g dry weight (Palanisamy et al., 2022), a value roughly 3.4 times higher than the iron content of dried spinach (Chan et al., 2019). However, caution should be exercised when interpreting these data, as although moringa leaves are relatively high in iron, their bioavailability is extremely low, and they can also inhibit the absorption of iron from other components of a meal, particularly at low dietary levels (Gallaher et al., 2017; Grosshagauer et al., 2021). Therefore, if moringa is to be used as an intervention food for anaemia, these bioavailability constraints need to be carefully considered.

Microgreens also exhibit beneficial cultivation characteristics, such as low space requirements that allow for rooftop gardens and vertical farms. Combined with rapid growth cycles and minimal fertiliser use, these traits make them suitable for both urban farming environments that experience spatial limitations (Singh et al., 2024; Teng et al., 2023). Further, microgreens are among the most economically viable crops produced via vertical farms because of their short growth cycle and the highly controlled environment in which they are grown (Amici et al., 2025).

However, rapid post-harvest decay drives up microgreen prices and limits their market primarily to local customers. It is therefore impossible to establish long-distance supply chains for microgreens without a sophisticated cold chain system. Therefore, they are not suitable as long-distance supply chain crops compared to more processed alternatives, such as moringa leaf powder, which last for at lasts for at least 12 months when stored properly (Kannangara et al., 2018).

Furthermore, a critical gap remains in the clinical data validating the long-term health benefits of microgreens. Current evidence supporting systemic antioxidant, anti-inflammatory, and anti-diabetic effects is based on *in vitro* studies or through animal models rather than rigorous human trials (Kainikkara et al., 2025). Currently, there is no research published on the chronic supplementation of microgreens specifically through human clinical trials (Henry et al., 2025). However, preliminary *in vitro* and animal studies have established multiple positive health effects of microgreens (Bhaswant et al., 2023; Henry et al., 2025; Kaya & Yardimci, 2025) and these preliminary findings must be translated through human clinical research to determine their therapeutic potential in adolescent cohorts.

8. Challenges, Limitations, and Future Research Directions

8.1. Microbial Safety and Quality Control

Moreover, the ideal temperature and humidity levels not only assist the development of microgreens but also increase the occurrence of pathogens, such as *Salmonella enterica, Escherichia coli* O157:H7, and *Listeria monocytogenes* (Barańska et al., 2025; Turner et al., 2020; Xavier et al., 2025). The contamination frequently originates within the seeds themselves, and once pathogens get into the plant vascular system, post-harvest cleaning cannot eliminate them (Rao et al., 2025). Consequently, the strict adoption of Good Agricultural Practices (GAPs) must be mandatory in order to reduce these microbiological risks. Standard GAP protocols would include the use of pathogen-tested seeds, irrigation water sanitisation, equipment sanitisation, and proper harvesting procedures (Vincent et al., 2015). It is also be necessary to transition to sterile growing media, like coco coir and hemp mats, to eliminate soil-borne pathogens.

8.2. Bioavailability and Clinical Evidence Gaps

Microgreens appear promising in terms of enhancing the bioavailability of iron based on *in vitro* and compositional evidence; however, randomised controlled trials (RCTs) evaluating the clinical effectiveness of microgreens in improving iron bioavailability have not yet been conducted on healthy adolescents. Currently, there is limited data on the bioavailability of iron and other red blood cell-boosting micronutrients in microgreen-based meals. Similarly, no studies have demonstrated a dose-dependent relationship between microgreen consumption and improvements in haemoglobin, serum ferritin, or transferrin saturation levels in adolescent females with iron deficiency. The next step is to establish and execute properly designed clinical trials with sufficient sample sizes to be able to create evidence-based public health policies using the currently available compositional data.

8.3. Standardisation of Bioactive Content

Microgreens differ from pharmaceutical drugs in that their phytochemical composition can vary significantly due to a wide variety of factors. These include species selection, seed genotype, choice of growing medium (soil vs hydroponic), light spectrum and intensity, temperature, irrigation volume, timing of harvesting stage, and post-harvest handling practices (Bantis, 2021; Dereje et al., 2023; El-Nakhel et al., 2020; Partap et al., 2023; Saleh et al., 2022). Because of this biological variability, it has been extremely difficult to develop standardised dietary guidelines and reproduce claims regarding the nutritional value of microgreens (Bhaswant et al., 2023; Kaya & Yardimci, 2025). However, advances in precision agriculture, such as the use of Artificial Intelligence (AI) for environmental control systems, the optimisation of light spectra through the use of LED lighting, and adjustment of nutrient solutions to enhance plant growth, are helping to improve this nutritional consistency of microgreens

(Borrelli et al., 2026; Gill et al., 2025; Gupta et al., 2023). Therefore, there is a great need for harmonisation of regulatory standards across large markets for all functional foods derived from microgreens.

8.4. Consumer Acceptance and Cultural Integration

Successful dietary interventions must be acceptable to the target population. Adolescents represent a particularly challenging subgroup of the population owing to the strong peer influence, social media, and commercial and digital marketing on food choices and dietary preferences (Chung et al., 2021). Studies using descriptive sensory evaluation and product testing specifically within adolescent populations in each target LMIC setting are necessary to identify microgreen species and preparation methods that optimise preferences, palatability and nutritional efficacy.

Recipe selection decisions that are made through co-design processes involving adolescents, their families, and school food service staff, and based on local cuisine traditions tend to be more successfully adopted and followed than decisions made through a top-down process with unfamiliar foods. To maximise the impact, any dietary intervention program must integrate nutrition education carried out through schools, which serves as the primary avenue for implementation. Education programs that help adolescents understand iron metabolism, the functions of vitamin C and carotenoids, the inhibitory role of tea and dairy products in restricting iron uptake, and the biochemical benefits of traditional food processing (such as soaking, germination, and fermentation), will enable adolescents to independently adopt and sustain healthy eating practices beyond the timeline of the program.

9. An Integrated Framework: Microgreens in Adolescent Anaemia Prevention

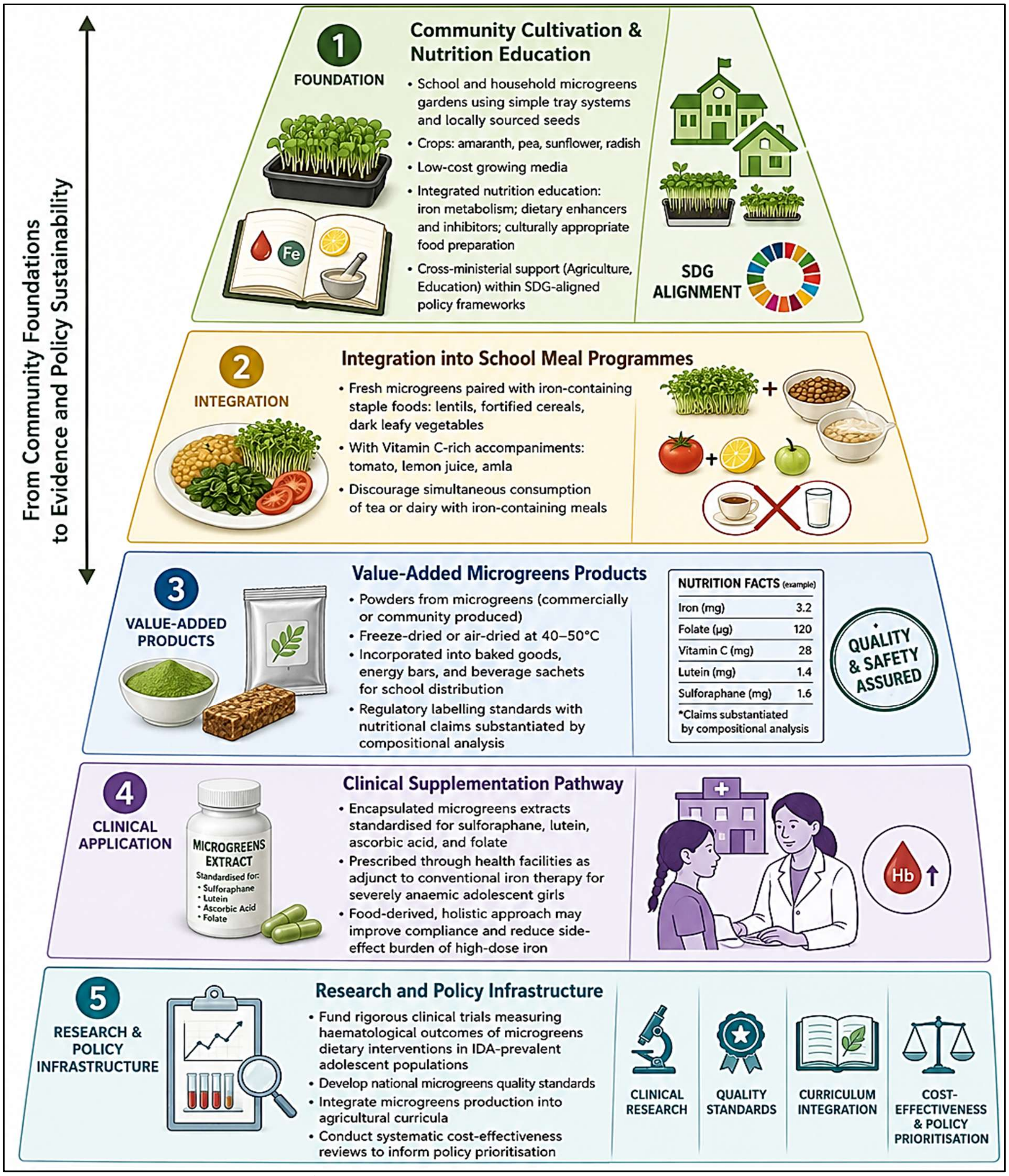
9.1. Integrated Framework for Policy Implementation

Based on the synthesis of existing evidence, the following five-tier integrated framework (Figure 4) for the prevention of anaemia among adolescents through the use of microgreens is suggested. The first tier focuses on community-based cultivation using school and family-based microgreen gardens utilising tray systems, local seed sources such as amaranth, pea, sunflower, and radish, and inexpensive growing media. The first-tier framework cannot be decoupled from educational curricula on iron metabolism, dietary factors that inhibit or enhance iron absorption, and culturally adapted food preparation techniques. It necessitates the involvement of ministries of agriculture and education at the national level through policies aligned with the SDGs.

Building on this foundation, the intermediate tiers address dietary integration and product innovation across varying levels of infrastructural capacity. Tier 2 concerns the systematic integration of fresh microgreens into school meal programmes. This is achieved by deliberately pairing them with iron-containing staple foods (such as lentils, fortified cereals, and dark leafy vegetables) and Vitamin C-rich accompaniments (including tomato, lemon juice, and amla), while actively discouraging the concurrent consumption of tea or dairy products as part of programme guidance. In situations where access to fresh microgreens is limited, Tier 3 entails the inclusion of value-added microgreen-based products (such as microgreen powder; commercially-produced or community-manufactured, in either freeze-dried or air-dried form, at 40-50°C) into baked products, energy bars, and beverages in sachets distributed to schools. This tier complies with labelling regulations requiring nutritional claims made on the product packaging to be backed up by an analysis of its chemical composition. For those suffering the most from the disease, Tier 4 suggests the provision of clinical supplements involving the use of microgreens extract capsules standardised for their levels of iron, SFN, lutein, ascorbic acid, and folate. They will be used to complement standard treatment of severe anaemia based on iron deficiency among adolescent females.

The final tier (Tier 5) addresses the research and policy support necessary to enable functioning of the previous four tiers. It involves the need for funding clinical studies measuring the impacts on haematological parameters of the interventions implemented in adolescent girls experiencing high prevalence of IDA, the establishment of standards related to microgreen quality in all countries, incorporation of microgreen production skills into agriculture education, and a comprehensive cost-effectiveness review aimed at prioritising policy-making decisions. Moreover, the effective implementation of the aforementioned tiers would call for the introduction of a parallel mechanism for programme evaluation based on haemoglobin concentration, serum ferritin level measured against World Health Organisation (WHO) age/sex-specific cut-offs, programme coverage rate, minimum dietary diversity score measured using (Minimum Dietary Diversity for Women) MDD-W tool, and other process indicators such as training completion rates. In case of resources allowing for longitudinal cohorts follow-up, it should be done to obtain comparative effectiveness data seen as one of Tier 5 priorities. Importantly, Tiers 1-5 cannot be viewed as a stepwise progression but rather as a selection of contextually relevant intervention options according to the infrastructure present in each country. Thus, while Tiers 1 and 2 can be implemented in low-income countries without significant capital inputs, Tiers 3 and 4 demand better-developed agri-food chain and presence of primary health care facilities, respectively. This way, the proposed structure reflects an equity-by-design strategy, with the two easiest-to-implement tiers targeted specifically at population with the highest anaemia prevalence.

This tiered architecture draws on established precedent, including the WHO's Stepwise Framework for micronutrient supplementation and national school feeding models such as India’s PM-POSHAN Scheme (formerly known as the Mid-Day Meal Scheme) and Brazil's PNAE, whilst extending them to incorporate a cultivable, whole-food micronutrient source whose production can be embedded within school infrastructure, thereby reducing dependency on the external supply chains that have historically constrained centrally procured supplementation programmes. Taken together, the five tiers constitute a coherent, mutually reinforcing system. Within this framework, community cultivation generates the supply and literacy that meal integration requires; value-added products sustain consumption patterns in resource-constrained contexts; clinical supplementation addresses severe cases that population-level tiers cannot reach; and the research and policy tier provides the empirical evidence base upon which the framework's long-term viability depends. Ultimately, microgreens' unique cultivability, affordability, nutritional density, and cultural adaptability position them as a versatile intervention capable of operating meaningfully across all five levels simultaneously.



IDA = Iron Deficiency Anaemia; SDGs = Sustainable Development Goals.

Figure 4. Integrated Framework for Microgreens-Based Adolescent Anaemia Prevention- A Five Tier Cascade from Community Cultivation to Research Governance

9.2. Dual Anaemia – Mental Health Intervention

Beyond haematological correction, microgreens address IDA's under-recognised mental health consequences which are critical for adolescent development (Figure 5). The replenishment of iron results in increased dopamine production and myelination, while folates and B-vitamins increase neurotransmitter metabolism (Hare et al., 2013). Concurrently, SFN and polyphenols play their part in decreasing neuroinflammation (Jalouli et al., 2025). This multi-nutrient profile contributes towards making microgreens a comprehensive nutritional strategy for tackling SDG 3 (health and well-being) and SDG 3.4, which specifically aims to promote mental health. Programs that promote microgreen intake at schools could result in additional benefits such as higher attendance rates due to improved cognitive abilities, decreased drop-out rates due to improved moods, and higher academic performance due to improved executive function. Consequently, the incorporation of microgreens into adolescent nutrition programs is vital, particularly in locations that suffer from both IDA and mental health concerns (such as South Asia and sub-Saharan Africa).

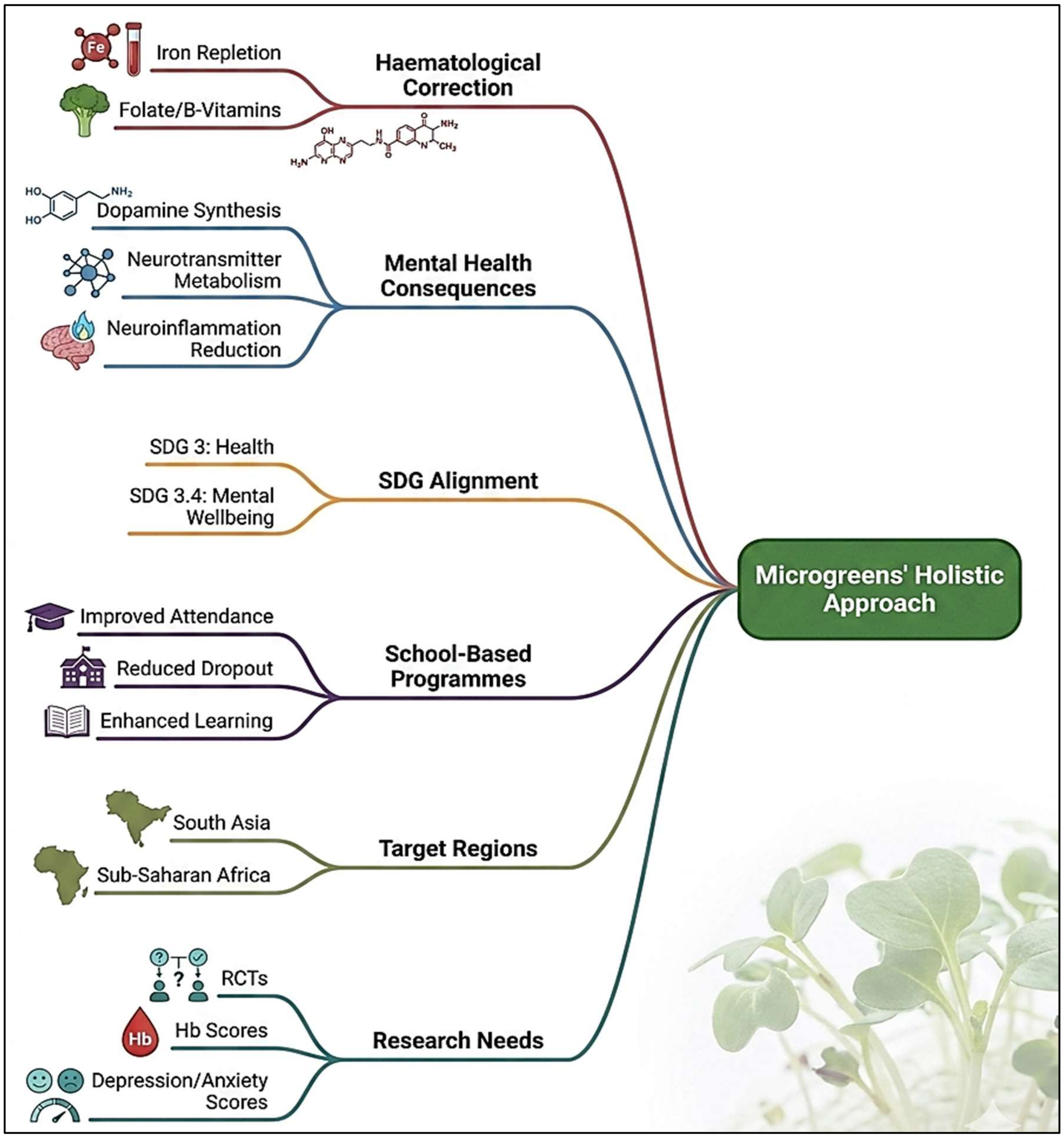


Figure 5. Microgreen's Holistic Approach to Iron-Deficiency Anaemia

10. Conclusion

IDA among adolescent girls is an intricate problem involving haematological, cognitive, and psychological factors that has been notoriously difficult to combat with traditional single-nutrient approaches and requires holistic solutions. This review presents a scientifically sound rationale for the use of microgreens as a powerful, culturally sensitive, and environmentally sustainable complementary intervention against anaemia in adolescents. High concentrations of folate, neuroprotective SFN, ascorbic acid, carotenoids, bioavailable iron, and synergistic phytonutrients make microgreens uniquely qualified to deliver iron along with the necessary biochemical support for maximum efficacy, metabolic assistance that traditional supplementation lacks.

Apart from their high nutritive value, microgreens illustrate the concept of sustainable nutrition as they are easy to cultivate locally with negligible environmental footprints, compatible with diverse cultural culinary practices, and scalable from household gardens to commercial farms. As such, microgreens are able to help overcome IDA via improved non-haem iron absorption, provide neuroprotection via iron-supported myelination and dopamine synthesis, and protect against internalising disorders, such as depression and anxiety, by virtue of their combined folate and B-vitamin profiles. Furthermore, the relevance of microgreens to SDGs 2, 3, 3.4, 12, and 13 places them firmly on the map of solutions to IDA and other problems associated with malnutrition.

Specific areas for further research include conducting *in vivo* clinical trials to measure the effects of microgreen-enriched diet on anaemic status among anaemia-prevalent adolescent populations; RCTs investigating the combined effect of these interventions on both haemoglobin and depression/anxiety levels in South Asia and sub-Saharan Africa are also necessary. Furthermore, future initiatives should focus on developing standard procedures for cultivating and processing microgreens to maintain consistent composition, undertaking sensory optimisation studies with adolescent populations, and establishing regulatory standardisation with regards to microgreen-based functional foods. Schools present themselves as an optimal platform to launch microgreen interventions as they unite the fields of agriculture, nutrition, and meals into a single system.

The convergence of a mounting global IDA burden, growing functional food science, and expanding urban vertical farming capacity creates a unique window of opportunity to position microgreens as a mainstream component of adolescent health policy. Realising this potential will require coordinated investment from governments, agricultural agencies, food industries, education and the research community. Stakeholders must be united by the recognition that sustainable, food-based solutions offer a resilient path to eliminating nutritional anaemia, other micronutrient deficiencies, while safeguarding cognitive, mental and physical health of the generation that will define our collective future.

Author Contributions

Conceptualization, writing and editing: W.S.K; Conceptualization, writing and editing: RU.

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Disclaimer (Artificial Intelligence)

The author(s) hereby declare that artificial intelligence technologies, including Large Language Models (e.g., ChatGPT, Copilot), were utilized in the structuring and editing of this manuscript and visual AI such as Napkin AI and ChatGPT were used exclusively to generate images, figures and tables based on the article's contextual content.

Competing Interests

Authors have declared that no competing interests exist.

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