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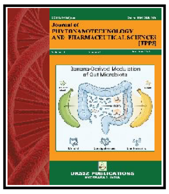

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Microgreens: Emerging phytochemical powerhouses for chronic disease management

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Abstract

Microgreens are tender, edible seedlings harvested at the cotyledonary to early true-leaf stage (7-21 days after germination) and are increasingly recognized as nutrient-dense functional foods. Comparative studies indicate that microgreens may contain 4-40 times higher concentrations of certain vitamins and carotenoids than their mature counterparts, depending on species and growth conditions. For example, red cabbage microgreens have been reported to contain significantly elevated levels of vitamin C (up to 147 mg/100 g fresh weight) and total phenolics exceeding 1000 mg gallic acid equivalents/100 g fresh weight. Brassicaceae microgreens are particularly rich in glucosinolates, with sulforaphane precursors ranging between 2-5 fold higher than mature leave. The dense phytochemical composition, including phenolic acids, flavonoids, carotenoids (β-carotene, lutein) and essential minerals (Fe, Zn, Mg), contributes to strong antioxidant activity, often demonstrating 20-50 per cent greater radical scavenging capacity in DPPH and FRAP assays compared to mature vegetables. Mechanistically, bioactive compounds in microgreens modulate oxidative stress and inflammatory pathways through NF-κB suppression and Nrf2 activation, thereby reducing cellular damage associated with chronic diseases. Emerging in vitro and in vivo studies demonstrate improvements in lipid profiles (10-25% reduction in LDL oxidation) and significant inhibition of a-amylase and a-glucosidase enzymes (15-35%), suggesting potential benefits in diabetes and cardiovascular disease management. Despite promising biochemical and preclinical evidence, well-designed human clinical trials remain limited. Given their rapid growth cycle, minimal resource requirements and high bioactive compound density, microgreens represent a sustainable and scalable dietary strategy for chronic disease prevention and integrative healthcare. Further standardized clinical investigations are required to validate dosage, safety and long-term therapeutic efficacy.

1. Introduction

Chronic non-communicable diseases (NCDs), notably cardiovascular diseases, diabetes mellitus, cancer, obesity and neurodegenerative disorders, constitute nearly 74 per cent of global mortality and represent a profound public health challenge. Their etiopathogenesis is intricately linked to persistent oxidative stress, low-grade systemic inflammation, metabolic dysregulation, endothelial dysfunction and compromised cellular detoxification mechanisms. Consequently, dietary interventions emphasizing phytochemical-dense functional foods have garnered substantial scientific interest as preventive and adjunct therapeutic strategies. Within this framework, microgreens have emerged as a compelling category of nutrient-concentrated edible plants with significant translational relevance in chronic disease mitigation. Microgreens are juvenile vegetable seedlings harvested at the cotyledonary to first true-leaf stage, typically within 7-21 days post-germination. Distinct from sprouts (consumed at an earlier developmental phase) and baby greens (harvested at a more advanced stage), microgreens exhibit an exceptional phytochemical density relative to their biomass. Comparative compositional analyses have demonstrated 4-40-fold higher concentrations of vitamins C, E and K, as well as carotenoids, in selected microgreens compared to their mature counterparts on a fresh weight basis (Xiao *et al*., 2012). Phytochemical biosynthesis in microgreens is influenced by genotype, taxonomic family, agronomic conditions and harvest timing. Species within the Brassicaceae family, including broccoli, red cabbage and kale, are particularly enriched in glucosinolates and their hydrolytic derivatives, notably sulforaphane. Quantitative assessments indicate glucosinolate concentrations ranging from 20-120 mg per 100 g fresh weight, frequently surpassing levels observed in mature foliage (Dereje *et al*., 2023). Sulforaphane is a potent activator of the nuclear factor erythroid 2-related factor 2 (Nrf2) signaling pathway, facilitating transcriptional upregulation of phase II detoxification enzymes and reinforcing endogenous antioxidant defense systems. In addition to glucosinolates, microgreens constitute abundant sources of phenolic acids, flavonoids, anthocyanins and carotenoids. Total phenolic content in red cabbage and amaranth microgreens has been reported to reach 800-1200 mg gallic acid equivalents per 100 g fresh weight, corresponding with robust radical-

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scavenging capacity (Bhaswant *et al*., 2023). Antioxidant potential, as quantified by DPPH and FRAP assays, is frequently 20-50 per cent greater than that of mature vegetables (Sharma *et al*., 2022). Kale microgreens, for instance, contain 6-10 mg per 100 g fresh weight of β-carotene and lutein, compounds implicated in ocular protection and cardiovascular risk attenuation (Podsêdek *et al*., 2024). Mechanistically, microgreen-derived phytochemicals modulate multiple molecular targets implicated in chronic disease progression. Polyphenols exert direct antioxidant effects through reactive oxygen species (ROS) scavenging and metal ion chelation, while also attenuating lipid peroxidation. Sulforaphane suppresses nuclear factor kappa B (NF-κB) activation, thereby downregulating pro-inflammatory mediators such as TNF-α and IL-6 (Sharma *et al*., 2022). Emerging evidence underscores antidiabetic properties, with in vitro studies demonstrating 15-35 per cent inhibition of á-amylase and α-glucosidase by extracts of fenugreek, radish and broccoli microgreens (Sola *et al*., 2024). *In vivo* models further reveal improvements in fasting glycemia and lipid profiles following dietary supplementation (Gupta *et al*., 2023), plausibly mediated through enhanced insulin sensitivity and modulation of carbohydrate metabolism. Cardioprotective effects have likewise been documented. Microgreen-enriched diets have been associated with 10-25 per cent reductions in oxidized low-density lipoprotein (LDL) and improved endothelial biomarkers in experimental systems (Choe *et al*., 2022). Additionally, intrinsic mineral constituents such as potassium and magnesium, alongside dietary nitrates contribute to vascular homeostasis and blood pressure regulation. Although, preclinical findings and mechanistic data are compelling, clinical substantiation remains comparatively limited. Most human investigations are characterized by small sample sizes and short intervention durations, precluding definitive conclusions regarding long-term therapeutic efficacy (Kaya *et al*., 2025). Rigorous randomized controlled trials, standardized cultivation protocols and comprehensive bioavailability analyses are imperative to translate experimental insights into evidence-based nutritional recommendations (Alrifai *et al*., 2026). Collectively, microgreens represent a highly concentrated repository of bioactive phytochemicals with demonstrable antioxidant, anti-inflammatory, antidiabetic, cardioprotective and potential chemopreventive properties. Their agronomic efficiency and adaptability to controlled-environment agriculture further reinforce their strategic value within sustainable and preventive nutrition paradigms.

Table 1: Phytochemical composition of selected microgreens

Microgreen species	Total phenolics (mg GAE/ 100 g FW)	Vitamin C (mg/100 g FW)	Total carotenoids (mg/100 g FW)	Glucosinolates (mg/100 g FW)	References
Broccoli (*Brassica oleracea*)	600-950	80-120	3-6	25-110	Xiao *et al*., 2012; Dereje *et al*., 2023
Red cabbage (*Brassica oleracea* var. capitata)	800-1200	100-147	4-7	30-95	Xiao *et al*., 2020; Bhaswant *et al*., 2023
Kale (*Brassica oleracea* var. acephala)	650-980	70-110	6-10	20-85	Podsêdek *et al*., 2024
Amaranth (*Amaranthus tricolor*)	750-1050	60-90	3-5	-	Sarker and Oba, 2022
Fenugreek (*Trigonella foenum-graecum*)	500-800	45-75	2-4	-	Sharma *et al*., 2022
Radish (*Raphanus sativus*)	550-900	65-100	3-6	40-120	Kyriacou *et al*., 2021

2. Phytochemical composition of microgreens

Microgreens are increasingly recognized as concentrated sources of bioactive phytochemicals due to their early developmental stage and high metabolic activity. During germination and early seedling growth, plants synthesize and accumulate elevated levels of secondary metabolites that function in defense and stress adaptation. Recent review studies indicate that microgreens frequently contain higher concentrations of phenolics, flavonoids, glucosinolates, carotenoids, vitamins and essential minerals compared to their mature vegetable counterparts (Kyriacou *et al*., 2021; Zhang *et al*., 2021; Renna *et al*., 2023). This enhanced phytochemical density has positioned microgreens as promising functional foods with antioxidant, anti-inflammatory and chemopreventive potential.

2.1 Phenolic compounds

Phenolic compounds constitute one of the most abundant phytochemical groups in microgreens. These compounds are synthesized *via* the phenylpropanoid pathway and include phenolic acids such as gallic acid, caffeic acid, ferulic acid, chlorogenic acid and p-coumaric acid. The concentration of total phenolic content (TPC) in microgreens is strongly influenced by species, genotype and environmental factors, particularly light quality and nutrient availability. Brassicaceae microgreens such as broccoli, radish and mustard have been reported to exhibit especially high phenolic levels (Xiao *et al*., 2012; Kyriacou *et al*., 2021). Phenolic compounds contribute significantly to antioxidant capacity through hydrogen atom donation and free radical scavenging mechanisms, thereby reducing oxidative stress associated with chronic diseases (Renna *et al*., 2023).

2.2 Flavonoids

Flavonoids are a major subclass of phenolics widely distributed in microgreens. These include flavonols (quercetin and kaempferol), flavones (luteolin and apigenin) and anthocyanins, particularly abundant in red and purple microgreens such as red cabbage and amaranth. Flavonoid biosynthesis is modulated by environmental cues, especially light spectrum, where blue and UV light stimulate accumulation (Zhang *et al*., 2021). Recent reviews emphasize that flavonoids in microgreens exhibit strong antioxidant, anti-diabetic and anti-inflammatory activities, supporting their inclusion in health-promoting diets (Renna *et al.*, 2023). Anthocyanin-rich microgreens also demonstrate enhanced radical scavenging activity and improved sensory appeal.

2.3 Glucosinolates and isothiocyanates

Glucosinolates are sulphur containing secondary metabolites predominantly present in Brassicaceae microgreens. Upon tissue disruption, these compounds are hydrolyzed by the enzyme myrosinase into biologically active derivatives such as isothiocyanates, nitriles and thiocyanates. Broccoli microgreens, in particular, are recognized for their high glucoraphanin content, which converts to sulforaphane, a compound widely studied for its chemopreventive properties (Xiao *et al.*, 2012; Kyriacou *et al.*, 2021). Isothiocyanates activate phase II detoxification enzymes and modulate the Nrf2 signaling pathway, contributing to cellular protection against carcinogens and oxidative damage (Renna *et al.*, 2023). Comparative studies have demonstrated that glucosinolate levels in microgreens can be several times higher than in mature plants.

2.4 Carotenoids

Carotenoids are lipid-soluble pigments localized in plastids and include β-carotene, lutein, zeaxanthin and violaxanthin. These compounds function in photoprotection during early plant development and provide provitamin A activity in humans. Green microgreens such as spinach, pea and sunflower are significant sources of β-carotene and lutein (Xiao *et al.*, 2012). Recent investigations confirm that microgreens contain appreciable carotenoid concentrations that contribute to antioxidant defense and eye health (Zhang *et al.*, 2021). Environmental factors, particularly light intensity and spectrum, strongly influence carotenoid biosynthesis in controlled cultivation systems.

2.5 Vitamins and minerals

Microgreens are valuable sources of vitamins such as ascorbic acid (vitamin C), tocopherols (vitamin E), phylloquinone (vitamin K) and folates, along with essential minerals including potassium, calcium, magnesium, iron and zinc. Comparative analyses reveal that several microgreen species exhibit higher vitamin C and vitamin E concentrations than their mature vegetable counterparts (Xiao *et al.*, 2012; Kyriacou *et al.*, 2021). The mineral profile depends largely on seed reserves and growth medium composition. The dense micronutrient content of microgreens makes them promising dietary supplements for addressing nutrient deficiencies and enhancing antioxidant status (Renna *et al.*, 2023).

Table 2: Nutritional comparison between selected microgreens and mature vegetables

Crop	Growth stage	Vitamin C (mg/100 g FW)	β-carotene (mg/100 g FW)	Total phenolics (mg GAE/100 g FW)	References
Broccoli	Microgreen	90-120	3.5-5.0	600-950	Xiao *et al.*, 2012; Kyriacou *et al.*, 2021
Broccoli	Mature vegetable	60-80	1.5-2.0	250-400	Xiao *et al.*, 2012
Red cabbage	Microgreen	100-147	4-7	800-1200	Bhaswant *et al.*, 2023; Xiao *et al.*, 2012
Red cabbage	Mature vegetable	55-65	2-3	300-450	Kyriacou *et al.*, 2021
Kale	Microgreen	70-110	6-10	650-980	Podsêdek *et al.*, 2024
Kale	Mature vegetable	40-60	3-4	250-420	Podsêdek *et al.*, 2024
Radish	Microgreen	65-100	3-6	550-900	Kyriacou *et al.*, 2021
Radish	Mature vegetable	25-35	1-2	150-300	Kyriacou *et al.*, 2021

Table 3: Phytochemical profile of selected microgreens with mechanisms and health implications

Microgreen species	Major phyto-chemical class	Key bioactive compounds	Mechanism of action	Health implications	References
Broccoli	Glucosinolates	Glucoraphanin, Sulforaphane	Activation of Nrf2 pathway; induction of phase - II detoxification enzymes	Chemopreventive, antioxidant, anti-inflammatory	Xiao *et al.*, 2012; Kyriacou *et al.*, 2021
Radish	Phenolics, Anthocyanins	Cyanidin derivatives, Caffeic acid	Free radical scavenging; of inflammatory mediators inhibition	Anti-inflammatory, antioxidant	Renna *et al.*, 2023
Red Cabbage	Flavonoids	Quercetin, Kaempferol, Anthocyanins	Modulation of cytokine expression; ROS neutralization	Cardioprotective, anti-cancer	Zhang *et al.*, 2021
Amaranth	Phenolics, Carotenoids	Betacyanins, β-carotene	Antioxidant activity; membrane stabilization	Anti-aging, immune enhancement	Kyriacou *et al.*, 2021
Pea	Carotenoids, Vitamins	Lutein, Ascorbic acid	Singlet oxygen quenching; immune modulation	Eye health support, antioxidant	Xiao *et al.*, 2012
Mustard	Glucosinolates	Sinigrin, Allyl isothiocyanate	Enzyme induction; anti-microbial activity	Detoxification, antimicrobial	Renna *et al.*, 2023

2.6 Bioactive peptides and other secondary metabolites

Beyond classical phytochemicals, germination processes in microgreens stimulate enzymatic hydrolysis of storage proteins, leading to the formation of bioactive peptides with potential antihypertensive and antioxidant activities. Emerging evidence suggests that microgreens also contain saponins, alkaloids, terpenoids, phytosterols and chlorophyll derivatives, which may contribute to antimicrobial and metabolic regulatory effects (Kyriacou *et al.*, 2021; Renna *et al.*, 2023). Although, research on these compounds remains limited, their presence further enhances the nutraceutical significance of microgreens.

3. Factors influencing phytochemical accumulation in microgreens

The phytochemical composition of microgreens is shaped by a constellation of genetic, environmental and agronomic factors. Because microgreens are harvested during early seedling development, even minor variations in cultivation conditions can lead to significant differences in the abundance of phenolic compounds, flavonoids, glucosinolates, carotenoids, vitamins, minerals and other bioactive metabolites (Bhaswant *et al.*, 2023; Cowden *et al.*, 2024). Therefore, understanding these influential factors is critical both for optimizing nutritional quality and for developing cultivation protocols tailored to specific phytochemical targets.

3.1 Genetic factors: Species and cultivar variation

The genetic makeup of a microgreen species or cultivar is a primary determinant of its phytochemical potential. Different taxa inherently possess divergent biosynthetic pathways, seed storage reserves and regulatory networks that influence metabolite accumulation during germination and early growth. For example, Brassicaceae microgreens such as broccoli and mustard are consistently documented to contain elevated glucosinolate levels, whereas pigmented Amaranthaceae and Brassicaceae genotypes often show higher flavonoid and anthocyanin concentrations (Kyriacou *et al.*, 2021; Bhaswant *et al.*, 2023). This genotype-specific variation underscores the importance of cultivar selection or breeding for enhanced nutraceutical quality in microgreen production.

3.2 Light quality, intensity and photoperiod

Light spectrum and intensity significantly influence phytochemical biosynthesis, acting through photoreceptors and signal transduction pathways that activate key enzymes in secondary metabolite pathways. Blue and ultraviolet wavelengths are particularly effective in inducing phenolic and flavonoid synthesis by stimulating phenylalanine ammonia-lyase and other regulatory enzymes, while red or mixed red-blue spectrums often enhance carotenoids and vitamins depending on species and developmental stage (Cowden *et al.*, 2024; Lee *et al.*, 2023). Manipulation of LED light spectra has therefore become a standard strategy in controlled-environment agriculture to modulate both phytochemical composition and biomass yield (Cowden *et al.*, 2024).

3.3 Growing medium, nutrient supply and biofortification

The chemical composition of the growing medium and nutrient solution exerts strong influence on mineral uptake, metabolic balance and phytochemical synthesis. Hydroponic and soilless growing systems allow for precise control of nutrient concentrations, leading to more uniform and predictable phytochemical profiles. Elevated nitrogen often favors primary growth at the expense of secondary metabolite synthesis, whereas targeted micronutrient supplementation such as selenium or iron can increase antioxidant responses and enrich nutritional content without reducing harvestable biomass (Mezeyová *et al.*, 2022; Tavan *et al.*, 2024). Biofortification approaches that strategically alter nutrient solutions thus provide pathways to enhance functional quality while maintaining yield integrity.

3.4 Elicitation and controlled abiotic stress

Controlled application of mild abiotic stressors known as elicitation has been demonstrated to stimulate phytochemical accumulation by triggering defence-related signalling pathways. Moderate levels of salinity, osmotic stress, temperature fluctuation and UV exposure have been shown to increase concentrations of phenolics, flavonoids and glucosinolates in several microgreen species, though excessive stress can reduce overall biomass and degrade labile compounds (Renna *et al.*, 2023). The non-linear nature of stress responses necessitates careful calibration of elicitor intensity and timing to maximize nutraceutical benefit without compromising yield.

3.5 Harvest stage and ontogeny

The developmental stage at harvest exerts a pronounced effect on phytochemical levels in microgreens. Comparative studies have found that metabolite profiles change rapidly as seedlings progress from the cotyledonary stage to the first true leaves and that peak concentrations of specific compounds, for example, certain phenolics or glucosinolates may occur at distinct phases depending on species and growing conditions (Ortiz *et al.*, 2024). Therefore, determining the optimal harvest window for each genotype and desired phytochemical target is essential to maximizing functional quality in commercial production.

3.6 Post-harvest handling and storage

Because microgreens have delicate tissues and high respiration rates, post-harvest handling has a major influence on the retention of phytochemicals. Vitamin C, some carotenoids, and phenolic compounds are particularly susceptible to degradation during storage and transport. Rapid pre-cooling, cold storage (typically around 4°C), minimal mechanical injury and modified-atmosphere packaging have all been shown to slow phytochemical loss and preserve overall quality (Turner *et al.*, 2020; Cowden *et al.*, 2024). An integrated approach combining pre-harvest enhancement with optimized post-harvest protocols is therefore necessary to deliver consistent nutritional benefits to consumers.

3.7 Interactions among factors and precision cultivation

Importantly, the factors described above do not act independently; they interact in complex ways. For example, light spectrum can modulate nutrient uptake and interact with elicitation responses, whereas genotype×environment interactions often determine whether a particular microgreen cultivar responds positively to a given spectral regime or nutrient strategy (Bhaswant *et al.*, 2023). This complexity highlights the value of precision cultivation systems that integrate genotype selection, tailored environmental control (light, temperature, nutrients), and optimized harvest strategies to consistently maximize desired phytochemicals. Emerging sensor-assisted and model-based control systems enhance the feasibility of such precision approaches in commercial plant factories and vertical farms.

4. Mechanisms of action in chronic disease prevention

Microgreens exert protective effects against chronic non-communicable diseases through multiple molecular and biochemical pathways. Their dense concentration of phenolics, flavonoids, glucosinolates, carotenoids, vitamins and bioactive peptides enables them to influence oxidative stress, inflammatory signaling, metabolic enzyme activity and gene expression. These mechanisms collectively contribute to the prevention of cardiovascular diseases, diabetes, obesity, neurodegeneration and cancer (Bhaswant *et al.*, 2023; Renna *et al.*, 2023). Understanding these mechanistic pathways provides a scientific foundation for the functional food potential of microgreens.

4.1 Antioxidant mechanisms

Oxidative stress arises from an imbalance between reactive oxygen species (ROS) production and antioxidant defense systems. Excess ROS contributes to lipid peroxidation, DNA damage, protein oxidation and cellular dysfunction, ultimately leading to chronic disease progression. Microgreens are rich in antioxidant compounds such as phenolic acids, flavonoids, anthocyanins, carotenoids, vitamin C and vitamin E, which neutralize ROS through direct and indirect mechanisms (Kyriacou *et al.*, 2019). Direct antioxidant mechanisms include hydrogen atom donation, electron transfer and metal ion chelation. Indirect mechanisms involve upregulation of endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx). Sulforaphane derived from broccoli microgreens activates the Nrf2 (nuclear factor erythroid 2–related factor 2) pathway, enhancing transcription of phase II detoxification and antioxidant genes (Renna *et al.*, 2023). Carotenoids such as β-carotene and lutein quench singlet oxygen and stabilize cellular membranes, further reducing oxidative damage (Lee *et al.*, 2023). Collectively, these mechanisms reduce oxidative burden and delay chronic disease onset.

4.2 Anti-inflammatory pathways

Chronic low-grade inflammation is a central driver of metabolic syndrome, cardiovascular disorders, neurodegeneration and certain cancers. Bioactive compounds in microgreens modulate inflammatory pathways at the molecular level. Flavonoids and isothiocyanates inhibit pro-inflammatory cytokines such as TNF-α, IL-6 and IL-1β and suppress activation of nuclear factor kappa B (NF-κB), a key transcription factor regulating inflammatory gene expression (Bhaswant *et al.*, 2023). Sulforaphane has been shown to interfere with NF-κB signaling while simultaneously activating Nrf2-mediated cytoprotective responses, creating a dual anti-inflammatory and antioxidant effect (Renna *et al.*, 2023). Anthocyanins present in pigmented microgreens reduce inflammatory mediator production and oxidative stress-induced inflammation. These combined effects attenuate vascular inflammation, improve endothelial function and reduce systemic inflammatory burden.

4.3 Modulation of metabolic enzymes

Microgreens influence metabolic pathways associated with glucose and lipid metabolism. Phenolic compounds and flavonoids have demonstrated inhibitory activity against carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, thereby reducing postprandial glucose spikes and improving glycemic control (Bhaswant *et al.*, 2023). Additionally, certain flavonoids modulate AMP-activated protein kinase (AMPK), enhancing insulin sensitivity and promoting glucose uptake in peripheral tissues. Glucosinolates and their derivatives have been associated with improved lipid metabolism through the regulation of cholesterol biosynthesis and fatty acid oxidation pathways. Bioactive peptides generated during germination may exert angiotensin-converting enzyme (ACE) inhibitory activity, contributing to blood pressure regulation (Turner *et al.*, 2020). Through these metabolic enzyme interactions, microgreens support the prevention of diabetes, obesity and cardiovascular disorders.

4.4 Epigenetic and gene regulatory effects

Emerging research indicates that phytochemicals present in microgreens can influence gene expression and epigenetic modifications. Sulforaphane and other isothiocyanates act as histone deacetylase (HDAC) inhibitors, thereby modulating chromatin structure and gene transcription associated with detoxification and tumor suppression (Renna *et al.*, 2023). This epigenetic modulation contributes to cancer chemoprevention by promoting the expression of protective genes and suppressing oncogenic pathways. Polyphenols and flavonoids also regulate microRNA expression, influencing cellular signaling pathways involved in apoptosis, cell proliferation and metabolic regulation. Through modulation of transcription factors such as Nrf2, NF-κB and peroxisome proliferator-activated receptors (PPARs), microgreens exert broad regulatory control over gene networks implicated in chronic disease development (Bhaswant *et al.*, 2023). These gene-regulatory mechanisms highlight the molecular depth of microgreens' therapeutic potential.

5. Role in chronic disease management

Chronic non-communicable diseases (NCDs), including cardiovascular diseases, diabetes mellitus, obesity, cancer and neurodegenerative disorders, account for the majority of global morbidity and mortality. Dietary strategies emphasizing functional foods rich in bioactive phytochemicals have gained increasing attention in disease prevention and management. Microgreens, owing to their concentrated levels of phenolics, flavonoids, glucosinolates, carotenoids, vitamins, minerals and bioactive peptides, have emerged as promising dietary components for mitigating chronic disease risk (Bhaswant *et al.*, 2023; Renna *et al.*, 2023). Their multifaceted biological activities contribute to metabolic regulation, antioxidant defense, inflammation control and gene modulation, thereby supporting chronic disease management.

5.1 Cardiovascular diseases

Cardiovascular diseases (CVDs) remain the leading cause of mortality worldwide and are closely linked to oxidative stress, dyslipidemia, hypertension and endothelial dysfunction. Microgreens contribute to cardiovascular health through multiple mechanisms. Phenolic compounds and flavonoids reduce oxidative modification of low-density lipoprotein (LDL), thereby decreasing atherogenic risk (Kyriacou *et al.*, 2019). Glucosinolates and their hydrolysis products, particularly sulforaphane, enhance endothelial function and reduce vascular inflammation by activating Nrf2-mediated antioxidant pathways (Renna *et al.*, 2023). Furthermore, potassium and magnesium present in microgreens support blood pressure regulation, while bioactive peptides formed during germination may exhibit angiotensin-converting enzyme (ACE) inhibitory activity, contributing to antihypertensive effects (Turner *et al.*, 2020). Animal studies have demonstrated improved lipid profiles and reduced oxidative stress markers following consumption of Brassicaceae microgreens (Xiao *et al.*, 2012). These combined effects suggest that inclusion of microgreens in daily diets may lower CVD risk.

5.2 Diabetes mellitus

Diabetes mellitus is characterized by chronic hyperglycemia resulting from impaired insulin secretion or action. Oxidative stress and inflammation significantly contribute to disease progression and complications. Microgreens may support glycemic control through several pathways. Flavonoids and phenolic acids inhibit carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, thereby attenuating postprandial glucose spikes (Bhaswant *et al.*, 2023). Additionally, antioxidant activity reduces oxidative damage to pancreatic β-cells.

Certain phytochemicals in microgreens activate AMP-activated protein kinase (AMPK), enhancing glucose uptake and improving insulin sensitivity (Renna *et al.*, 2023). High dietary fiber and micronutrient density further contribute to improved metabolic regulation. Although large-scale clinical trials remain limited, experimental and *in vitro* evidence supports the potential role of microgreens in diabetes prevention strategies.

5.3 Obesity and metabolic syndrome

Obesity and metabolic syndrome involve complex interactions among insulin resistance, dyslipidemia, chronic inflammation and oxidative stress. Microgreens offer low-calorie, nutrient-dense options that support weight management and metabolic balance. Polyphenols and flavonoids modulate adipogenesis by influencing transcription factors such as PPAR-γ and AMPK, thereby regulating lipid accumulation (Bhaswant *et al.*, 2023).

Glucosinolates and isothiocyanates may enhance lipid metabolism and reduce adipocyte differentiation. The high antioxidant capacity of microgreens mitigates oxidative stress-induced inflammation associated with adipose tissue dysfunction (Renna *et al.*, 2023). Inclusion of microgreens in balanced diets may therefore contribute to the prevention of obesity-related metabolic disturbances.

5.4 Cancer prevention and chemoprevention

Among the most extensively studied benefits of microgreens is their chemopreventive potential. Glucosinolates and their hydrolysis product sulforaphane play pivotal roles in cancer prevention by inducing phase II detoxification enzymes and promoting apoptosis in abnormal cells (Kyriacou *et al.*, 2019). Sulforaphane also inhibits histone deacetylases (HDACs), thereby modulating epigenetic regulation of tumor suppressor genes (Renna *et al.*, 2023). Anthocyanins and other flavonoids exhibit anti-proliferative effects by reducing oxidative DNA damage and inhibiting tumor cell growth. Carotenoids contribute to cellular membrane stabilization and immune surveillance enhancement. Experimental studies suggest that regular consumption of Brassicaceae microgreens may reduce carcinogen-induced tumor formation, though further human clinical studies are required to confirm these findings (Xiao *et al.*, 2012).

5.5 Neurodegenerative disorders

Neurodegenerative diseases such as Alzheimer's and Parkinson's disease are closely associated with oxidative stress, neuroinflammation and mitochondrial dysfunction. The antioxidant-rich profile of microgreens may help mitigate neuronal oxidative damage. Polyphenols and flavonoids can cross the blood-brain barrier and modulate neuronal signaling pathways involved in cognition and memory (Bhaswant *et al.*, 2023). Sulforaphane has demonstrated neuroprotective effects through activation of Nrf2 pathways and reduction of neuroinflammatory markers (Renna *et al.*, 2023). Carotenoids such as lutein have been linked to improved cognitive performance and protection against age-related cognitive decline. Although, clinical evidence specific to microgreens remains limited, the phytochemical composition suggests promising neuroprotective potential.

6. Bioavailability and pharmacokinetics of microgreen phytochemicals

The health-promoting effects of microgreens depend not only on their phytochemical composition but also on the bioavailability and pharmacokinetic behavior of these bioactive compounds. Bioavailability refers to the proportion of an ingested compound that is absorbed and becomes available at the site of physiological action. Pharmacokinetics involves absorption, distribution, metabolism and excretion (ADME) of these compounds within the body. Although, microgreens are rich in phenolics, flavonoids, glucosinolates, carotenoids, vitamins and bioactive peptides, their biological efficacy depends largely on their stability during digestion, intestinal absorption, biotransformation and systemic circulation (Bhaswant *et al.*, 2023; Renna *et al.*, 2023).

6.1 Absorption and gastrointestinal stability

Upon consumption, phytochemicals from microgreens undergo digestion in the gastrointestinal tract. Water-soluble compounds such as vitamin C and certain phenolic acids are generally absorbed in the small intestine through passive diffusion or active transport mechanisms. However, flavonoids often occur as glycosides and require enzymatic hydrolysis by intestinal β-glucosidases or gut microbiota before absorption (Manach *et al.*, 2020). Glucosinolates present in Brassicaceae microgreens are hydrolyzed by the enzyme myrosinase, producing bioactive isothiocyanates such as sulforaphane. If plant myrosinase is inactivated during processing, gut microbiota can contribute to hydrolysis, though conversion efficiency may vary (Bouranis *et al.*, 2023). Carotenoids are lipid-soluble and require dietary fats and bile salts for micelle formation prior to intestinal absorption (Rodriguez-Amaya, 2021).

6.2 Metabolism and biotransformation

After absorption, phytochemicals undergo phase I and phase II metabolism primarily in the liver. Phenolic compounds are commonly conjugated into glucuronides, sulfates, or methylated derivatives, which may retain biological activity (Manach *et al.*, 2020). Sulforaphane is rapidly conjugated with glutathione and metabolized *via* the mercapturic acid pathway, forming sulforaphane-N-acetylcysteine conjugates detectable in plasma and urine (Bouranis *et al.*, 2023). Carotenoids such as β-carotene are partially converted into retinol (vitamin A) in enterocytes, while others such as lutein and zeaxanthin are transported *via* lipoproteins and accumulate in specific tissues, including the retina (Rodriguez-Amaya, 2021). These metabolic transformations influence both bioactivity and systemic distribution.

6.3 Distribution and tissue targeting

Following absorption and metabolism, phytochemicals are distributed through systemic circulation. Lipid-soluble compounds (carotenoids, certain flavonoids) associate with lipoproteins and accumulate in adipose tissue, liver and neural tissues. Lutein and zeaxanthin are selectively deposited in the macula, contributing to visual and cognitive health (Rodriguez-Amaya, 2021). Sulforaphane metabolites have been detected in plasma within hours after consumption of broccoli microgreens, indicating rapid absorption and systemic availability (Bouranis *et al.*, 2023). Polyphenol metabolites may cross the blood-brain barrier and exert neuroprotective effects, though their concentrations in neural tissue are typically lower than in plasma.

6.4 Role of gut microbiota

The gut microbiome plays a critical role in modulating the bioavailability of microgreen phytochemicals. Microbial enzymes facilitate hydrolysis, reduction and deconjugation reactions that influence absorption efficiency and bioactivity. For example, unabsorbed flavonoids reaching the colon are metabolized into smaller phenolic acids with enhanced bioavailability (Manach *et al.*, 2020). Similarly, microbial myrosinase-like activity contributes to glucosinolate hydrolysis when plant enzymes are inactive. Inter-individual differences in gut microbiota composition may therefore lead to variability in therapeutic response following microgreen consumption.

7. Clinical and preclinical evidence supporting the health benefits of microgreens

Although microgreens are widely recognized for their rich phytochemical composition, translation of these properties into clinically relevant health outcomes requires robust preclinical and human studies. Current evidence includes *in vitro* experiments, animal model studies and a limited but growing number of clinical trials. Most available data focus on Brassicaceae microgreens, particularly broccoli, due to their high glucoraphanin and sulforaphane content (Renna *et al.*, 2023; Bhaswant *et al.*, 2023).

7.1 *In vitro* studies

In vitro studies have demonstrated strong antioxidant, anti-inflammatory, antimicrobial and antiproliferative activities of microgreen extracts. Phenolic-rich extracts from broccoli, red cabbage and radish microgreens exhibit high radical scavenging activity in DPPH and ABTS assays, indicating potent antioxidant potential (Kyriacou *et al.*, 2019). Cell culture studies further show that sulforaphane derived from broccoli microgreens induces apoptosis and inhibits proliferation in cancer cell lines by activating Nrf2 signaling and suppressing NF-κB pathways (Renna *et al.*, 2023). Anthocyanin-rich microgreens also demonstrate protective effects against oxidative stress-induced cellular damage. While *in vitro* findings provide mechanistic insights, their physiological relevance depends on bioavailability and achievable plasma concentrations *in vivo*.

Table 4: Clinical and preclinical evidence on health effects of microgreens

Study type	Model/population	Microgreen species/ compound	Dose/ intervention	Outcomes	References
In vitro	Human cancer cell lines	Broccoli microgreen extract (Sulforaphane -rich)	Concentration-dependent (µM range)	Induced apoptosis; Nrf2 activation; NF-κB inhibition	Renna *et al.*, 2023
In vitro	Oxidative stress cell model	Red cabbage microgreen phenolic extract	Extract-based	Reduced ROS; enhanced antioxidant enzyme activity	Kyriacou *et al.*, 2019
Animal study	Hyperlipidemic mice	Broccoli microgreens (whole diet inclusion)	10-15% diet supplementation	Reduced LDL oxidation; improved lipid profile; decreased oxidative stress markers	Xiao *et al.*, 2012
Animal study	Diabetic rodent model	Polyphenol-rich microgreen analogues	Extract supplementation	Improved fasting glucose; enhanced insulin sensitivity	Bhaswant *et al.*, 2023
Animal study	Neuroinflammation model	Sulforaphane (Brassica microgreens)	mg/kg body weight	Reduced neuroinflammatory cytokines; Nrf2 activation	Renna *et al.*, 2023
Human clinical trial	Healthy adults	Broccoli microgreens (glucoraphanin-rich)	Single-dose consumption	Detectable plasma and urinary sulforaphane metabolites (confirming bioavailability)	Bouranis *et al.*, 2023
Human intervention (related cruciferous vegetables)	Adults with metabolic risk	Glucosinolate-rich vegetables	Dietary intake over weeks	Reduced inflammatory biomarkers; improved detoxification enzyme activity	Renna *et al.*, 2023

7.2 Animal model studies

Preclinical animal studies provide stronger evidence for systemic health effects. Dietary supplementation with broccoli microgreens in hyperlipidemic mouse models has been associated with improved lipid profiles, reduced LDL oxidation and decreased markers of oxidative stress (Xiao *et al.*, 2012). These findings support cardioprotective potential. In diabetic rodent models, polyphenol-rich plant extracts comparable to microgreen compositions have demonstrated improved insulin sensitivity and reduced fasting blood glucose levels, suggesting possible antidiabetic effects (Bhaswant *et al.*, 2023). Additionally, sulforaphane supplementation in animal studies has shown neuroprotective effects by reducing neuroinflammation and oxidative neuronal damage (Renna *et al.*, 2023). Despite promising results, more animal studies specifically focusing on whole microgreen consumption rather than isolated compounds are needed to establish dose-response relationships and long-term safety.

7.3 Human clinical studies

Clinical evidence specifically evaluating microgreens is still limited but expanding. One notable study investigating broccoli microgreens demonstrated measurable increases in plasma and urinary sulforaphane metabolites following ingestion, confirming systemic bioavailability (Bouranis *et al.*, 2023).This finding supports translational relevance of glucoraphanin-rich microgreens. Human intervention studies involving cruciferous vegetables rich in glucosinolates show reductions in inflammatory biomarkers, improved detoxification enzyme activity, and potential cardiometabolic benefits (Renna *et al.*, 2023). Although, many trials focus on mature vegetables or isolated phytochemicals, the higher concentration of bioactive compounds in microgreens suggests comparable or enhanced effects at lower serving sizes. Large-scale randomized controlled trials specifically targeting microgreens remain scarce. Therefore, further well-designed clinical studies are required to confirm efficacy in chronic disease prevention and management.

8. Conclusion

Microgreens are emerging functional foods distinguished by high concentrations of phenolics, flavonoids, glucosinolates, carotenoids, vitamins, minerals and bioactive peptides (Kyriacou *et al.*, 2019; Renna *et al.*, 2023). These phytochemicals confer antioxidant, anti-inflammatory, cardioprotective, antidiabetic, chemopreventive and neuroprotective effects (Bhaswant *et al.*, 2023). Mechanistically, microgreen bioactives act through reactive oxygen species scavenging, activation of the Nrf2 pathway, inhibition of NF-κB signaling, modulation of metabolic enzymes such as α-amylase and AMPK and epigenetic regulation (Renna *et al.*, 2023; Manach *et al.*, 2020). Brassicaceae microgreens rich in glucoraphanin and sulforaphane are particularly relevant for cancer chemoprevention and detoxification (Bouranis *et al.*, 2023). Preclinical studies demonstrate benefits in cardiovascular, metabolic, and neurodegenerative models, while early clinical evidence confirms sulforaphane bioavailability; however, large-scale randomized trials on whole microgreens are still limited.

Beyond health benefits, microgreens support sustainable food systems due to their short growth cycle, adaptability to controlled environments and biofortification potential (Mezeyova *et al.*, 2022; Renna *et al.*, 2023). LED-based cultivation and nutrient optimization can further enhance phytochemical density (Zhang *et al.*, 2020). Nonetheless, issues related to shelf-life, microbial safety, scalability and regulatory standardization require further investigation (Turner *et al.*, 2020).

Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

S. J. Imamsaheb: Contributed to conceptualization, methodology design, supervision, and final approval of the manuscript. **D. Sreedhar:** Contributed to data curation, formal analysis, and drafting of the original manuscript.**K. H. Yashavantakumar:** Contributed to literature review, data organization, and critical revision of the manuscript.

Consent for publication

All authors gave their full consent for publication and submission to this journal.

Conflict of interest

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