Review Article

Phytochemical Diversity, Therapeutic Potential, and Nutraceutical Prospects of Underutilized Indian Leafy Herbs: Current Status, Advances, and Future Directions

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ABSTRACT

Underutilized edible leafy herbs form a critical yet often overlooked component of Indian diets and traditional medicine, offering a potent source of phytonutrients with diverse health benefits. This review evaluates eight such herbs *Moringa oleifera*, *Amaranthus viridis*, *Trigonella foenum-graecum*, *Solanum nigrum*, *Murraya koenigii*, *Mentha spicata*, *Basella alba*, and *Ipomoea aquatica*, focusing on their phytochemical profiles, pharmacological potential, and functional food applications. These species are rich in flavonoids, alkaloids, terpenoids, betalains, and saponins that exhibit antioxidant, antidiabetic, anti-inflammatory, hepatoprotective, and antimicrobial effects. Nutraceutical innovations, including nanoencapsulation, high-resolution metabolomic profiling (LC-MS, NMR), and green extraction methods, have enhanced the bioavailability and stability of these phytoconstituents. Despite strong *in vitro* and preclinical evidence, clinical trials and standardization protocols remain limited. This review identifies key research gaps and advocates for omics-integrated, sustainability-focused strategies to promote these herbs as climate-resilient, low-input crops for dietary diversification, nutrition security, and functional food development. The findings provide a roadmap to integrate Indian leafy greens into modern nutritional frameworks while preserving ethnobotanical heritage.

Keywords: Edible Indian leafy herbs, Phytochemicals, Nutraceutical applications, Sustainable nutrition, Bioactive compounds, Omics-guided food innovation

Highlights

- Evaluates eight underutilized Indian leafy herbs for their phytochemical diversity and therapeutic applications.
- Highlights bioactivities such as antioxidant, antidiabetic, hepatoprotective, and neuroprotective effects.
- Discusses omics-integrated strategies, nanoencapsulation, and green extraction for enhancing nutraceutical efficacy.
- Identifies research gaps in clinical validation, standardization, and bioavailability.
- Promotes these herbs as climate-resilient crops for sustainable nutrition and food security.

Introduction

The integration of plant-based foods into mainstream health care has gained significant global momentum, driven by increasing awareness of the limitations of synthetic drugs and the rising prevalence of chronic lifestyle disorders such as diabetes, obesity, cardiovascular disease, and cancer [1]. In this context, edible leafy herbs, often termed functional greens, have emerged as a promising reservoir of phytochemicals with both nutraceutical and pharmacological significance. India, a biodiversity hotspot with centuries of Ayurvedic and ethnobotanical wisdom, is home to a vast array of edible leafy plants such as *Moringa oleifera, Amaranthus viridis, Trigonella foenum-graecum*, and others. These herbs have been used for generations across diverse regional cuisines and cultures, not only for flavor and aroma but also for preventive and curative healthcare roles [2,3].

The nutritional and therapeutic value of these herbs lies in their rich profile of bioactive phytochemicals, including flavonoids, alkaloids, saponins, terpenoids, betalains, carotenoids, and polyphenols. These compounds exhibit antioxidant, anti-inflammatory, antidiabetic, hepatoprotective, and antimicrobial effects that can

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modulate various biochemical pathways linked to chronic disease progression [4,5]. Several studies have reported that leafy vegetables like *Moringa* and *Trigonella* contain phenolic acids and glucosinolates [6,7] that scavenge free radicals and regulate oxidative stress, while *Solanum nigrum* and *Basella alba* have shown liver-protective and hematopoietic effects, respectively [8,9,10]. Moreover, these herbs are gaining attention for their nutraceutical applications, being incorporated into teas, powders, capsules, and even functional foods such as fortified bread, juices, and soups [3].

Despite their potential, many of these edible leafy herbs remain underutilized or scientifically underexplored in terms of their bioavailability, clinical efficacy, and mechanisms of action. There is a growing need to systematically review and compile available phytochemical and pharmacological data to identify promising species for future plant-based nutraceutical development.

2. Botanical background and ethnobotanical significance

India’s floristic diversity includes a vast array of edible leafy herbs that form the foundation of both culinary and ethnomedical traditions. The following section presents ethnobotanical backgrounds, pharmacological relevance, and selected recent studies for the eight prioritised herbs. Phytochemical compositions and therapeutic activities have been summarized comparatively in Table 1.

Table 1. Comparative table of Indian edible leafy herbs

Botanical Name	Common Name	Key Phytochemicals	Therapeutic Effects	Nutraceutical Applications	Concerns / Research Highlights
Moringa oleifera	Drumstick tree	Quercetin, Kaempferol, Chlorogenic acid, Gallic acid, Isothiocyanates, Apigenin, Ferulic acid, Rutin (Salsabila & Salam, 2025)	Antioxidant, Antidiabetic, Antibacterial, Hepatoprotective, Anti-inflammatory (Parvin et al., 2025; Deepali et al., 2025)	Capsules, Functional teas, Fortified soups, Noodles, Health bars (Mahajan et al., 2023)	Stable post-processing; anticancer potential via isothiocyanates; limited clinical trials (Mahajan et al., 2023)
Amaranthus viridis	Slender amaranth	Betanin, Amaranthin, Rutin, Kaempferol, Isorhamnetin, Caffeic acid, Gallic acid (Sarker & Oba, 2020; Jaafar & Kadhim, 2025)	Hepatoprotective, Anti-inflammatory, Antioxidant, Antidiabetic (Peter & Gandhi, 2017)	Leaf powders, Teas, Fortified snacks, Smoothies (Sarker & Oba, 2020)	High phenolics; needs extraction standardization and safety validation (Jaafar & Kadhim, 2025)
Trigonella foenum-graecum	Fenugreek	Diosgenin, Yamogenin, Trigonelline, Choline, Quercetin, Galactomannans, Vitexin (Naidu et al., 2022; Sulieman et al., 2023)	Antidiabetic, Lactation support, Hypocholesterolemic, Anti-inflammatory, Neuroprotective (Rajalakshmi & Sethuraman, 2023)	Capsules, Nutrient bars, Functional beverages, Bread (Gupta et al., 2021)	Synergistic potential with turmeric, cinnamon; trigonelline/diosgenin well-standardized (Gupta et al., 2021)
Solanum nigrum	Black nightshade	Solanine, Solamargine, Kaempferol, Quercetin, Chlorogenic acid, Tannins, Î²-Sitosterol (Chen et al., 2022; Jamal et al., 2025)	Antioxidant, Hepatoprotective, Antimicrobial, Anticancer, Gastroprotective	Capsules, Functional extracts, Processed leaf powder (Elizalde-Romero et al., 2021; Asante, 2024)	Toxicity concerns with raw glycoalkaloids; proper cooking advised (Chidambaram et al., 2022)
Murraya koenigii	Curry leaf tree	Mahanimbine, Girinimbine, Koenimbine, Quercetin, Rutin, Ferulic acid, Essential oils (Dinesh et al., 2023)	Antidiabetic, Hypocholesterolemic, Antioxidant, Antimicrobial (Rajkumar et al., 2024)	Functional teas, Herbal blends, Instant curry mixes (Jain & Vyas, 2021)	Carbazole alkaloids unique; cardioprotective and GRAS status confirmed (Rajkumar et al., 2024)
Mentha spicata	Spearmint	Rosmarinic acid, Carvone, Menthol, Limonene, Luteolin, Apigenin, Hesperidin (Mocan et al., 2021)	Antioxidant, Antimicrobial, GI Support, Neurocognitive, Anti-inflammatory (Herrlinger et al., 2018; Ismail et al., 2023)	Capsules, Herbal teas, Lozenges, Functional beverages (Mocan et al., 2021)	Improves cognition; high variation in oil content by climate/harvest (Herrlinger et al., 2018)
Basella alba	Malabar spinach	Kaempferol, Rutin, Betacyanins (gomphrenins), Saponins, Mucilage, Î²-Carotene, Lutein (Sutor-Świeży et al., 2024)	Antioxidant, Antianemic, Anti-inflammatory, Antimicrobial, Anticancer (Karthika et al., 2022; Bose et al., 2023)	Iron-rich powders, Functional soups, Colorants	Betacyanins have colorant potential; mucilage supports GI healing (Bose et al., 2023)
Ipomoea aquatica	Water spinach	Quercetin, Rutin, Luteolin, Apigenin, Chlorogenic acid, Caffeic acid, Betacyanins, Saponins (Kunwar et al., 2021)	Antioxidant, Antidiabetic, Hepatoprotective, Anti-inflammatory, Anticancer, Antimicrobial (Saikia et al., 2023)	Functional powders, Natural antioxidants, Pigments, Nanoparticle delivery	Explored in detox beverages and nanoparticle carriers; strong in vitro efficacy

2.1 *Moringa oleifera* Lam. (Moringaceae)

Moringa oleifera, commonly known as drumstick tree or "Sahjan" in India, is a fast-growing deciduous tree native to the sub-Himalayan tracts. It is widely cultivated across India for its edible leaves, flowers, pods, and seeds, used for immunity enhancement, anemia correction, and fatigue management [6]. Studies have confirmed its antioxidant, hepatoprotective, and antidiabetic effects, with novel extraction technologies (e.g., membrane distillation) improving bioactive recovery [11]. However, translational research and randomized clinical trials remain limited [12].

2.2 *Amaranthus viridis* L. (Amaranthaceae)

Amaranthus viridis, commonly known as "green amaranth" or "slender amaranth," is a widely distributed leafy herb found across tropical and subtropical regions of India. Traditionally regarded as a diuretic, hepatoprotective, and anti-inflammatory plant, it has gained renewed attention for its high antioxidant potential and rich phytochemical reservoir [13]. LC-MS profiling has validated its functional food potential, though bioactive extraction and safety assessments require standardization [14].

2.3 *Trigonella foenum-graecum* L. (Fabaceae)

Commonly known as fenugreek or "methi," this herb is both a staple food additive and a classical Ayurvedic medicine across India and the Mediterranean region. Its galactomannan-rich seeds are used to manage diabetes, enhance lactation, and reduce serum lipids [15]. Emerging data also supports its neuroprotective role *via* acetylcholinesterase inhibition [16]. Synergistic nutraceutical formulations involving fenugreek and turmeric are under exploration [17].

2.4 *Solanum nigrum* L. (Solanaceae)

Solanum nigrum L. is a medicinal plant of wide ethnopharmacological relevance, distributed across Asia, Africa, and Europe. Black nightshade, or "Makoy," has historical use in liver ailments and ulcers. Its berries and leaves are sources of cytotoxic glycoalkaloids like solamargine and solanine [18]. These constituents exhibit anticancer and anti-inflammatory effects. Dietary use requires proper processing to mitigate toxicity from glycoalkaloids [8].

2.5 *Murraya koenigii* (L.) Spreng. (Rutaceae)

Murraya koenigii, commonly known as curry leaf tree, is a small tropical tree native to the Indian subcontinent. Its aromatic leaves are not only integral to South Indian cuisine but are also highly valued in Ayurvedic and Unani medicine systems for their digestive, antidiabetic, antioxidant, and antimicrobial properties with increasing pharmacological validation establishing its potential for functional food development and nutraceutical formulations [19]. Carbazole alkaloids such as mahanimbine have shown antioxidant and hypocholesterolemic activities in metabolic models [20,21]. Its GRAS status approves its application in fortified food and capsule-based nutraceuticals.

2.6 *Mentha spicata* L. (Lamiaceae)

Spearmint (*Mentha spicata*) is a perennial aromatic herb rich in monoterpenes that is widely cultivated across temperate and subtropical regions, including India. Its leaves are extensively used in culinary preparations such as chutneys, salads, and herbal infusions, and in traditional medicine as a digestive aid, carminative, and antimicrobial agent [22]. Rich in rosmarinic acid and carvone, it possesses antimicrobial, neurocognitive, and anti-inflammatory properties [23,24].

2.7 *Basella alba* L. (Basellaceae)

Basella alba L., commonly known as Malabar spinach or "poi saag" in India, is a perennial climber consumed as a leafy vegetable in tropical Asia and Africa. Traditionally, its leaves and stems have been employed for treating anaemia, constipation, inflammation, and ulcers, and also serves as a cooling agent in Ayurvedic medicine [25]. Pharmacological studies further confirm its antioxidant, antimicrobial, and wound healing activities [26,27], while LC–MS/MS profiling highlights gomphrenins and phenolic acids as key bioactives contributing to its nutraceutical value [28].

2.8 *Ipomoea aquatica* Forssk. (Convolvulaceae)

Ipomoea aquatica, commonly known as water spinach or "kalmi saag" in India, is a semi-aquatic perennial herb widely cultivated across Asia. It is highly valued as a nutritious leafy vegetable and traditional medicine, often prescribed for detoxification, anti-inflammatory effects, and anaemia management [29]. Recent investigations highlight its strong antioxidant and antimicrobial properties due to flavonoids and polyphenols [30,31], with growing evidence of its antidiabetic and hepatoprotective roles in animal models [32]. The therapeutic breadth of these herbs is directly linked to their rich phytochemical constitution.

3. Phytochemical composition and bioactive diversity

Indian edible leafy herbs exhibit a rich spectrum of secondary metabolites, which collectively support their nutritional and therapeutic potential. Among the most abundant classes are flavonoids (e.g., quercetin, kaempferol, luteolin), phenolic acids (e.g., chlorogenic, caffeic, ferulic acids), alkaloids (e.g., carbazole and glycoalkaloids), saponins, betalains, and terpenoids. These phytochemicals contribute synergistically to antioxidant, anti-inflammatory, and metabolic regulatory effects. Notably, *Moringa oleifera* leaves contain up to 75 mg/100 g dry weight (DW) of quercetin and 50–60 mg/100 g DW of chlorogenic acid, while *Trigonella foenum-graecum* seeds offer 2–3% diosgenin and ~100 mg/100 g DW of trigonelline [7,33]. *Basella alba* is a significant source of gomphrenins, with betacyanin content ranging from 35-48 mg/100 g fresh weight (FW) depending on the cultivar and maturity stage [28].

Figure 1 shows the schematic representation of phytochemical mechanisms of action. The antioxidant properties of these compounds stem from their ability to donate hydrogen atoms, chelate metal ions, and modulate redox signaling pathways. Flavonoids and polyphenols enhance endogenous antioxidant enzyme activities specifically superoxide dismutase (SOD), glutathione peroxidase (GPx), and catalase thereby mitigating oxidative damage. In addition, alkaloids, such as mahanimbine in *Murraya koenigii* and solamargine in *Solanum nigrum*, display cytotoxic, hypoglycemic, and anti-inflammatory actions through redox modulation and membrane interaction mechanisms. Phytochemical variability among species and across regions remains a key challenge. For instance, the betalain content of *Amaranthus viridis* and saponin levels in *Trigonella foenum-graecum* can vary significantly due to environmental, seasonal, and post-harvest conditions. Standardization using high-resolution LC-MS/MS and NMR-based metabolomics is increasingly employed to characterize bioactive fingerprints for quality control and formulation design [11].

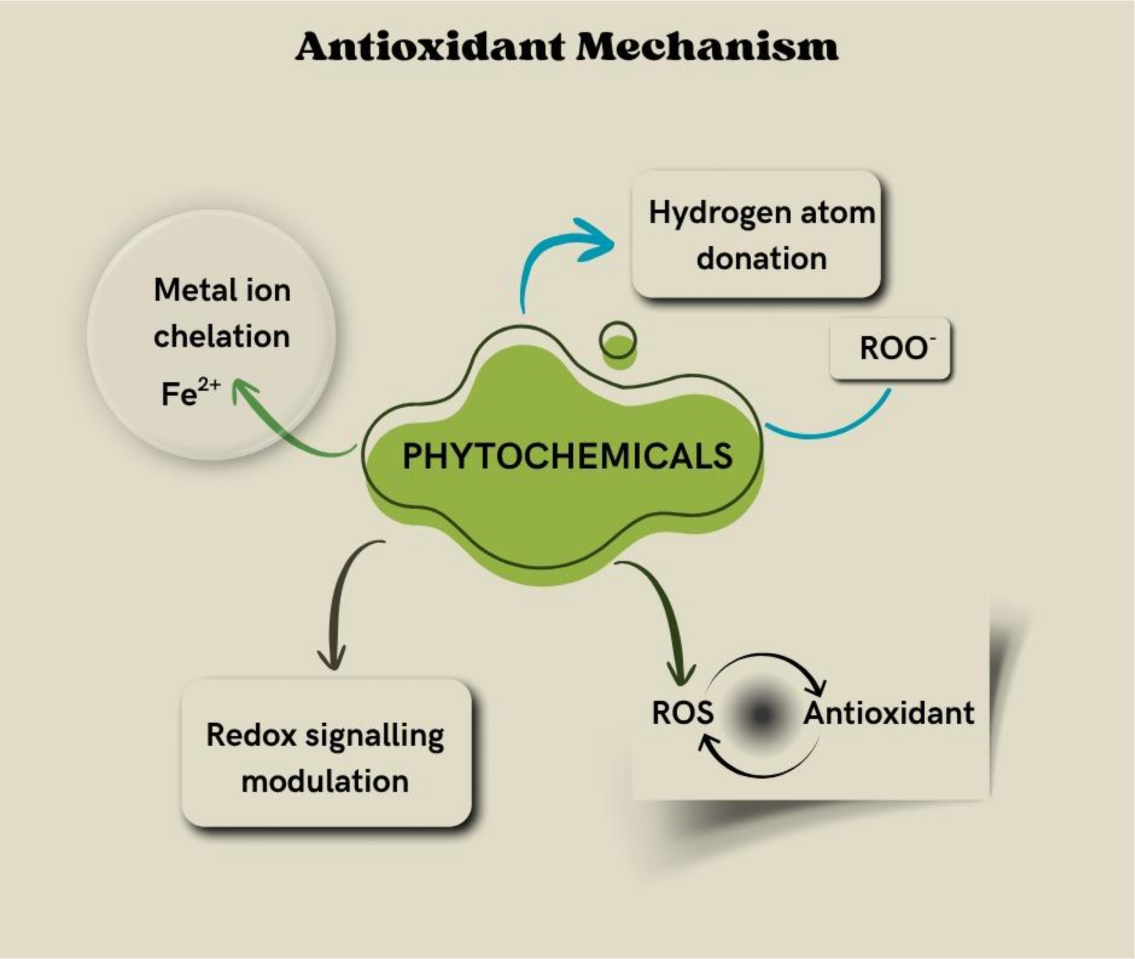

Figure 1. The schematic representation of phytochemical mechanisms of action

4. Therapeutic activities and pharmacological evidence

The therapeutic potential of Indian edible leafy herbs is strongly linked to their diverse phytochemical repertoire. Extensive *in vitro*, *in vivo*, and limited clinical studies have demonstrated activities ranging from antioxidant and anti-inflammatory to antidiabetic, hepatoprotective, antimicrobial, and anticancer effects (Table 2). A synthesis of evidence for major pharmacological domains is presented below.

4.1 Antioxidant and cytoprotective activities

Flavonoid- and polyphenol-rich extracts from *Moringa oleifera*, *Amaranthus viridis*, and *Solanum nigrum* demonstrate potent antioxidant capacities through free radical scavenging and metal chelation mechanisms. Enhanced enzymatic antioxidant defenses by upregulating SOD, GPx, and catalase have been reported following administration of aqueous and ethanolic extracts leading to reductions in lipid peroxidation and DNA oxidative damage [34,35]. Quercetin, chlorogenic acid, and betacyanins contribute significantly to these effects, reducing lipid peroxidation and oxidative DNA damage [4, 2]. In particular, *Basella alba* and *Amaranthus viridis* extracts show high DPPH and FRAP scavenging activities, validating their nutritional use for oxidative stress mitigation [26,36].

4.2 Anti-inflammatory and hepatoprotective effects

Leaf extracts from *Murraya koenigii*, *Trigonella foenum-graecum*, and *Ipomoea aquatica* exhibit strong anti-inflammatory effects mediated via inhibition of cyclooxygenase-2 (COX-2) and lipoxygenase (LOX) pathways and suppression of pro-inflammatory cytokines such as tumor necrosis factor-alpha and interleukin-6 [37,21]. The hepatoprotective potential of *Solanum nigrum* is well established, as ethanolic extracts restore hepatic enzyme levels and reduce lipid peroxidation in CCl_4-induced hepatotoxicity models [9]. Likewise, decoctions of *I. aquatica* protect hepatic tissues from toxin-induced injury, corroborating its traditional detoxification uses [29]. Together, these studies substantiate traditional claims that these greens support liver and systemic anti-inflammatory health.

4.3 Antidiabetic and metabolic regulation

Hypoglycemic effects are among the best-documented therapeutic activities. *Trigonella foenum-graecum* demonstrates glycemic regulation *via* multiple mechanisms: its galactomannans slow glucose absorption, while trigonelline enhances insulin sensitivity. Human clinical trials have confirmed significant reductions in HbA1c and fasting glucose following fenugreek supplementation [38,39]. *Moringa oleifera* extracts inhibit α-amylase and α-glucosidase, thereby reducing postprandial hyperglycemia [6]. **M. koenigii** alkaloid-rich extracts additionally modulate lipid metabolism, reducing LDL and triglyceride levels [21], while **A. viridis** improves hepatic antioxidant defense in hyperglycemic models [13].

4.4 Antimicrobial activity

Antimicrobial studies highlight broad-spectrum effects across the eight herbs. *Moringa oleifera* aqueous and methanolic extracts inhibit *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa* [6]. Essential oils of *Mentha spicata* display membrane-disruptive effects on pathogenic bacteria [40]. **Murraya koenigii** and **Basella alba** extracts exhibit notable bactericidal and antifungal actions attributed to carbazole alkaloids and saponins [26]. Similarly, **Solanum nigrum** demonstrates broad-spectrum antimicrobial effects against both Gram-positive and Gram-negative bacteria, reinforcing ethnomedicinal applications in infection control [41, 42].

4.5 Emerging anticancer potential

Preclinical studies reveal anticancer potential for several herbs. Glycoalkaloids such as solamargine in *Solanum nigrum* induce apoptosis and cell cycle arrest in breast and cervical cancer cell lines [18,43]. *Moringa oleifera* seed isothiocyanates are under investigation for chemopreventive properties [11]. *Basella alba* methanolic extracts inhibit proliferation of colorectal cancer cells through apoptotic mechanisms [44], while *Ipomoea aquatica* phytochemicals such as luteolin and chlorogenic acid demonstrate cytotoxic activity against colon and breast cancer models [45].

Table 2. Therapeutic activities of the Indian edible leafy herbs

Herb	Major Bioactives	Therapeutic Activities
Moringa oleifera	Quercetin, Chlorogenic acid, Isothiocyanates	Antioxidant, Antidiabetic, Antibacterial, Hepatoprotective
Amaranthus viridis	Betalains, Rutin, Isorhamnetin, Phenolic acids	Hepatoprotective, Antioxidant, Anti-inflammatory, Antidiabetic
Trigonella foenum-graecum	Trigonelline, Diosgenin, Galactomannans	Antidiabetic, Lactogenic, Hypocholesterolemic, Neuroprotective
Solanum nigrum	Solamargine, Solanine, Chlorogenic acid	Antioxidant, Hepatoprotective, Antimicrobial, Anticancer, Gastroprotective
Murraya koenigii	Mahanimbine, Koenimbine, Carbazole alkaloids	Antidiabetic, Hypocholesterolemic, Antioxidant, Antimicrobial
Mentha spicata	Rosmarinic acid, Carvone, Menthol	Antioxidant, Antimicrobial, Gastroprotective, Neurocognitive

4.6 Neurocognitive and other emerging effects

Recent studies highlight the neurocognitive benefits of *Mentha spicata*, with supplementation of its standardized extract shown to significantly enhance working memory and attention span in human clinical trials [24]. *Trigonella foenum-graecum* shows neuroprotective effects via acetylcholinesterase inhibition, indicating relevance for Alzheimer's disease prevention [16]. Other emerging effects include wound healing (via mucilage fractions of *Basella alba*), hypolipidemic effects of *Murraya koenigii*, and gastrointestinal relief from *Mentha spicata*, all of which merit further investigation through clinical trials.

5. Nutraceutical applications and functional food integration

The incorporation of traditional leafy herbs into modern food systems has led to a new generation of nutraceutical and functional food products that merge traditional wisdom with contemporary dietary science. Owing to their dense phytochemical and micronutrient composition, species such as **Moringa oleifera**, **Trigonella foenum-graecum**, and **Basella alba** have transitioned from household remedies to commercially validated nutraceutical ingredients. Across India, these herbs are being incorporated into capsules, teas, fortified flours, and meal replacements aimed at managing oxidative stress, diabetes, anemia, and hyperlipidemia [3]. For instance, **Moringa oleifera** leaf powder is a common additive in immunity-boosting health mixes and fortified noodles, while **T. foenum-graecum** extracts are standardized for trigonelline and diosgenin in glucose-control supplements. Similarly, **Basella alba** and **Amaranthus viridis** are utilized in iron-enriched beverages and soups targeted at combating nutritional anemia [46].

The increasing availability of encapsulated, freeze-dried, and microencapsulated herbal extracts has further enhanced stability and bioaccessibility of key phytoconstituents such as quercetin, diosgenin, and betacyanins. Green encapsulation methods such as freeze-drying, nanoencapsulation, and biopolymer conjugation represent eco-friendly approaches to enhance stability and delivery of bioactives, aligning with sustainable functional food development. Additionally, **Mentha spicata** and **Murraya koenigii** essential oils are now widely incorporated into herbal teas and functional beverages for digestive and metabolic health [47]. The growing nutraceutical market reflects the integration of these herbs into health-oriented food innovations, bridging ethnomedicinal relevance with clinical nutrition. Table 3 summarizes their current applications, bioactive classes, and commercial product examples.

Table 3. Nutraceutical and functional food applications of Indian leafy herbs

Herb	Primary Bioactives	Nutraceutical Format / Product	Health Application	Key References
Moringa oleifera	Quercetin, chlorogenic acid, isothiocyanates	Leaf powders, fortified soups, capsules	Antioxidant, antidiabetic, immunity booster	Mahajan et al., 2023; Sarkar & Oba, 2023
Amaranthus viridis	Betalains, phenolics, flavonoids	Herbal teas, leaf powders, soups	Hepatoprotective, antioxidant, antidiabetic	Sarker & Oba, 2020
Trigonella foenum-graecum	Trigonelline, diosgenin, galactomannans	Capsules, functional beverages, fortified flour	Hypoglycemic, hypolipidemic, lactogenic	Rajalakshmi & Sethuraman, 2023; Naidu et al., 2022
Solanum nigrum	Solamargine, flavonoids, phenolic acids	Extracts, capsules, herbal decoctions	Hepatoprotective, anticancer, antimicrobial	Elizalde-Romero et al., 2021; Jamal et al., 2025
Murraya koenigii	Carbazole alkaloids, flavonoids, essential oils	Functional teas, herbal tablets, curry leaf mixes	Antidiabetic, hypocholesterolemic, antioxidant	Rajkumar et al., 2024; Jain & Vyas, 2021
Mentha spicata	Carvone, rosmarinic acid, polyphenols	Herbal teas, lozenges, functional beverages	Digestive, antimicrobial, antioxidant	Ismail et al., 2023; Mocan et al., 2021
Basella alba	Betacyanins, saponins, iron, folate	Iron-enriched beverages, soups, natural colorants	Antianemic, antioxidant, anti-inflammatory	Adegoke & Ojo, 2017; Lakshmi et al., 2019
Ipomoea aquatica	Quercetin, luteolin, chlorogenic acid	Leaf extracts, supplements, fortified drinks	Antidiabetic, hepatoprotective, detoxifying	Kunwar et al., 2021

6. Role in food security and sustainable nutrition

Indian edible leafy herbs not only contribute to cultural and culinary diversity but also hold immense relevance in addressing the challenges of food security, nutritional deficiencies, and sustainability. Many of these herbs, particularly *Basella alba*, *Ipomoea aquatica*, and *Amaranthus viridis*, are underutilised despite their micronutrient density, bioactive phytochemicals, and low-input cultivation requirements. Promoting their wider use in daily diets and functional foods can serve as a cost-effective strategy to mitigate malnutrition and hidden hunger.

6.1 Nutrient security and hidden hunger

Hidden hunger, characterized by deficiencies in essential micronutrients such as iron, calcium, and vitamin A, remains prevalent in several Indian populations [48]. Herbs such as *Basella alba* (rich in iron and folate), *Moringa oleifera* (rich in vitamins A and C), and *Ipomoea aquatica* (noted for polyphenols and minerals) have been shown to significantly improve hematological and antioxidant status when incorporated into diets [10,31]. Their nutritional density underscores their role as functional greens for population-level dietary interventions.

6.2 Agronomic resilience and sustainability

Several leafy herbs demonstrate high resilience to drought, pests, and poor soils. For instance, *Amaranthus viridis* and *Basella alba* require minimal agronomic inputs, while *Ipomoea aquatica* thrives in semi-aquatic systems, providing food security in flood-prone regions [36,29]. Cultivation of these species in marginal lands and home gardens enhances local food availability and reduces reliance on market-purchased vegetables.

6.3 Contribution to dietary diversity

Traditional ethnobotanical surveys indicate region-specific use of wild leafy vegetables for gastrointestinal, respiratory, and hematinic disorders [2]. Integrating these herbs into mainstream diets diversifies nutritional intake, reduces dependence on calorie-dense staples, and supports cultural dietary heritage. Such approaches align with sustainable diet frameworks promoted by global health agencies.

6.4 Empowering rural livelihoods

Promotion of cultivation and commercialization of these herbs can create value chains for rural farmers, particularly women's cooperatives engaged in leaf powder processing, herbal teas, and fortified snack production [3]. Their market integration not only contributes to nutrition but also provides livelihood opportunities, thereby supporting socio-economic sustainability.

7. Challenges and research gaps

Despite strong ethnobotanical foundations and growing pharmacological validation, the integration of Indian edible leafy herbs into mainstream nutraceutical and functional food sectors remains constrained by several gaps.

- **Limited clinical validation**: Most evidence for antioxidants, antidiabetic, and hepatoprotective properties is derived from *in vitro* or animal studies [2,4]. Human clinical trials remain scarce, small in scale, and poorly standardized [39,18]. Larger, biomarker-based trials are urgently needed to establish dosage, efficacy, and safety.
- **Poor bioavailability of phytochemicals**: Flavonoids, saponins, and alkaloids often show rapid metabolism or low solubility, resulting in poor systemic exposure [2,4]. Without advanced formulations, therapeutic promise observed in laboratory studies may not translate to real-world efficacy.
- **Standardization challenges**: Phytochemical profiles vary widely with species, ecotype, soil, climate, and processing methods [11]. Betalain content in *Amaranthus viridis* [39, 49] or betacyanin levels in *Basella alba* [28] differ significantly between regions. Lack of validated quality markers and protocols hinders reproducibility and regulatory approval.
- **Toxicological concerns**: While safe in culinary doses, certain bioactives (e.g., glycoalkaloids in *Solanum nigrum*) can cause toxicity when consumed raw or in high concentrations [8]. Chronic intake of high fenugreek saponins has been linked to gastrointestinal discomfort [50]. Rigorous toxicological assessments across acute and chronic models are needed.
- **Erosion of traditional knowledge**: Indigenous practices regarding preparation, dosage, and synergistic herb combinations remain under-documented [3]. The loss of this heritage narrows opportunities for integrative, culturally grounded product development.

8. Future Directions

Harnessing the full potential of Indian leafy herbs demands a roadmap that combines modern science with sustainable and culturally sensitive strategies.

- **Integration of omics platforms**: Metabolomics, proteomics, and nutrigenomics can uncover novel bioactives and link them to disease-modifying pathways [2]. High-resolution LC-MS and NMR profiling should be expanded to build phytochemical databases [7,23], while nutrigenomic studies can tailor herb-based interventions to personalized nutrition.

- **Translational clinical research**: Future work should prioritize well-designed multicentric trials to confirm efficacy. Particular attention is needed for herbs like *Moringa oleifera*, *Trigonella foenum-graecum*, and *Basella alba*, focusing on metabolic, hepatic, and hematological outcomes [6,39,10].
- **Green delivery systems**: Novel, eco-friendly formulations such as nanoencapsulation, biopolymer conjugates, and metabolomics-guided profiling offer sustainable routes to improve the bioavailability and reproducibility of labile phytochemicals [51,11]. These strategies also strengthen the bioprospecting value of these greens.
- **Sustainable cultivation and climate-smart crops**: Underutilized herbs like *Basella alba* and *Ipomoea aquatica* thrive in low-input systems and stress-prone environments [29,36]. Promoting them in kitchen gardens, marginal lands, and urban farming can enhance local food sovereignty while diversifying diets.
- **Policy and commercialization pathways**: Establishing guidelines for safety, standardization, and labeling of herb-based nutraceuticals will accelerate adoption. Public-private partnerships, women-led cooperatives, and start-ups can drive value addition through teas, fortified snacks, herbal powders, and natural pigments [3, 46].

9. Conclusion

Indian edible leafy herbs represent a vital intersection of traditional dietary wisdom and contemporary scientific validation. Their multifaceted bioactivities, encompassing antioxidant, anti-inflammatory, metabolic, and hepatoprotective effects, affirm their dual role as both food and medicine. By consolidating phytochemical, pharmacological, and nutraceutical insights, this review underscores the potential of these greens to address nutrition-linked disorders through dietary and functional food interventions. However, translating these promising findings into scalable solutions requires more than laboratory validation. Rigorous clinical trials, standardized extraction protocols, and advanced metabolomic profiling are essential to ensure reproducibility, safety, and efficacy. Strengthening interdisciplinary collaboration between ethnobotany, food technology, and pharmacognosy will be crucial in realizing this goal. Sustainable cultivation and scientific validation of these underexploited herbs can simultaneously advance nutritional security and plant-based health innovation through interdisciplinary collaboration.

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Conflict of Interest

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Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Author Contributions

Debalina Kundu conceptualized the review, conducted the literature search, and wrote the manuscript. All co-authors (Nandita Das, Amartya Gupta, Abu Saleh Musha Islam and Rituparna Mukherjee) contributed to the curation of literature sources, critical review of the manuscript, and provided scientific inputs. All authors have read and approved the final version of the manuscript. The authors thank the anonymous reviewers in advance for their constructive insights.

Consent for Publication

All authors agreed to publish the manuscript in **Nutrition and Food in Health and Disease**

Data Availability

No new data was generated or analyzed in this study. Data sharing is not applicable to this article.

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