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Physicochemical, Functional, and Health-Promoting Properties of Processed Nettle (*Urtica Dioica*) Leaves: A Review

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ABSTRACT

Nettle (*Urtica dioica* L.) is gaining increasing attention as a nutrient-dense, bioactive-rich plant with promising applications in functional foods. However, the leaves are highly perishable after harvesting due to their high moisture content (75%–85%) and susceptibility to microbial deterioration. This review synthesizes current knowledge on the physicochemical properties, functional attributes, and food applications of processed nettle leaves. Nettles exhibit substantial bioactive composition including protein, dietary fiber, chlorophylls, carotenoids, and phenolic compounds. These constituents contribute to antioxidant, anti-inflammatory, antimicrobial, and metabolic-regulating activities, whereas processing methods such as freeze-drying and solvent extraction significantly influence bioactive retention. Numerous studies demonstrate the successful incorporation of nettle leaf powder and extracts into bakery products, beverages, dairy products, and nutraceuticals at substitution levels of up to 20%. Functional properties, including water- and oil-holding capacity, emulsifying ability, and color-enhancing potential, support nettle's suitability as a multi-functional food ingredient. However, challenges remain regarding sensory acceptability, variability in phytochemical composition due to processing and environmental factors, and limited standardization of extraction and drying techniques. To fully realize its potential in the food sector, future research should prioritize improving the bioavailability of key bioactive compounds and optimizing formulation strategies to enhance product quality, stability, and consumer acceptance.

1 | Introduction

Functional foods, defined as foods that provide physiological benefits beyond basic nutrition, are increasingly recognized as strategic dietary components for preventing and managing non-communicable diseases (NCDs) (Freihat et al. 2025; Shaikh 2022). These NCD conditions, including cardiovascular diseases, cancers, chronic respiratory disorders, and diabetes, continue to rise globally, prompting intensified interest in foods capable of modulating metabolic, oxidative, and inflammatory

pathways (Freihat et al. 2025; Mahajan et al. 2025; Shaikh 2022). The health-enhancing properties of functional foods derived from whole grains, fruits, and vegetables, are particularly valued for their rich bioactive composition of proteins, dietary fiber, essential fatty acids, phenolic acids, flavonoids, carotenoids, sterols, vitamins, and minerals, all of which exert synergistic effects on human health (Shaikh 2022). These phytochemicals contribute to antioxidant activity, glycemic regulation, cholesterol-lowering effects, immune modulation, and protection against cellular

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damage. Within this broad category, nettle (*Urtica* spp.) has emerged as an especially promising candidate due to its exceptionally dense profile of health-promoting constituents.

The genus *Urtica* belongs to the family Urticaceae, comprising approximately 54 genera and more than 2600 species distributed globally (Kregiel et al. 2018; Upton 2013). Among them, *Urtica dioica* is the most widespread and extensively studied species. It is subdivided into several subspecies including *U. dioica* subsp. *dioica* L. (common nettle), *U. dioica* subsp. *galeopsifolia* (fen nettle), and *U. dioica* subsp. *gracilis* (Aiton) Selander (American stinging nettle), which differ mainly in leaf morphology, trichome type, and ecological adaptation (Kregiel et al. 2018; Upton 2013). Specifically, common nettle (*U. dioica* L.) thrives in temperate and subtropical regions, favoring nitrogen-rich, moist soils and partial shade, and grows abundantly along riverbanks, forest margins, and disturbed lands (Bhusal et al. 2022; Parente et al. 2025). They can reach heights of 1–2 m, and the leaves are ovate to cordate with serrated margins, dark green adaxial surfaces, and paler abaxial sides, covered with stinging trichomes that release histamine, formic acid, and acetylcholine upon contact (Paulauskienė et al. 2021; Rutto et al. 2013). Although statistics on their global agricultural production are still unknown, the plant grows abundantly on marginal lands with minimal agronomic inputs, representing a sustainable and low-input resource for food, feed, and industrial applications (Di Virgilio et al. 2015; Shonte et al. 2020; Tanyitiku and Njombissie Petchu 2025).

Common nettle has a long ethnobotanical history as both a food and medicinal plant across Europe, Asia, Africa, and South America, where it has been traditionally harvested for its nutritional and therapeutic properties (Adhikari et al. 2016; Devkota et al. 2022; Diddana et al. 2021). Historical accounts indicate that in medieval Britain and Ireland, young nettle shoots were among the earliest spring vegetables consumed, often cooked into soups, purées, or stews to provide vital nutrients after winter scarcity (Bhusal et al. 2022; Guil-Guerrero et al. 2003). At present, the fresh tender leaves continue to be used as leafy vegetables or incorporated into salads, whereas dried nettle is commonly utilized in soups, bakery formulations, herbal infusions, and nutraceutical products (Alemayehu et al. 2016; Parente et al. 2025).

Recent phytochemical investigations have demonstrated that *Urtica dioica* leaves are characterized by a rich bioactive composition, including high levels of proteins, dietary fiber, essential vitamins (particularly provitamin A carotenoids, vitamins C and K, and several B-group vitamins), minerals (such as iron, calcium, magnesium, and potassium), and a wide range of phytochemicals including phenolic acids, flavonoids, chlorophylls, and carotenoids (Đurović, Micić, et al. 2023; Tola et al. 2025). In addition, nettle leaves possess a favorable fatty acid profile, characterized by relatively high proportions of polyunsaturated fatty acids, particularly α -linolenic (ω -3) and linoleic (ω -6) acids, which contribute to their nutritional and functional value (Đurović et al. 2017, 2018; Popov et al. 2020). These constituents contribute to its antioxidant, anti-inflammatory, and metabolic regulatory activities (Bhusal et al. 2022; Devkota et al. 2022; Sahal et al. 2025). Despite this promising biochemical profile, much of the existing

literature (Muceniec et al. 2025; N. Namazi et al. 2012; F. Namazi et al. 2018; Nassiri-Asl et al. 2009; Orčić et al. 2014; Parente et al. 2025) has focused predominantly on the phytochemical characterization of *U. dioica* within pharmacological and therapeutic contexts. For example, quercetin derived from *U. dioica* has been explored in pharmacological formulations for wound management, particularly in diabetic ulcers, due to its antimicrobial and healing-promoting properties (Zenão et al. 2017).

Given the expanding body of literature on the nutritional potential and bioactivities of nettle, a comprehensive review focusing specifically on processed nettle leaves and their suitability as food ingredients is timely. This review aims to synthesize current knowledge on processing approaches, physicochemical properties, and food applications of nettle, while also evaluating its potential health-promoting properties. It further highlights opportunities for incorporating nettle into diverse food systems and identifies key research gaps requiring further investigation.

2 | Processing Methods of Nettle Leaves

2.1 | Harvesting

Fresh nettle leaves (Figure 1) are typically harvested by hand using protective clothing and gloves to avoid irritation from the stinging trichomes. Harvesting is carried out from early spring to late summer (March to August), before flowering, when the accumulation of secondary metabolites and chlorophyll synthesis reach their peak (Kukric et al. 2012). After flowering, lignification of cell walls increases, and the formation of cystoliths (calcium carbonate crystals) contributes to a coarse texture and potential bitterness (Upton 2013). The nutritional composition of nettle leaves depends strongly on the plant's stage of maturity and time of harvest (Bhusal et al. 2022; Devkota et al. 2022; Kronbauer et al. 2023). For instance, Zhang



FIGURE 1 | Fresh leaves of stinging nettle (*Urtica dioica* L.).

et al. (2023) reported that the protein content of nettle leaves before flowering (27.4%) was higher than after flowering (20.7%). Consequently, harvest timing is a critical determinant of the nutritional value, functional ingredient potential, and associated health benefits of nettle-based products.

After harvesting, nettle leaves are highly perishable owing to their high moisture content (75%–85%), active enzymatic systems, and susceptibility to microbial deterioration (Adhikari et al. 2016; Shonte et al. 2020). Therefore, appropriate processing is essential to enhance product stability, preserve bioactive integrity, and improve their functionality and suitability for use in food and nutraceutical applications (Paulauskienė et al. 2021; Adhikari et al. 2016). In this context, two major processing routes have been established; conversion into leaf powder and extraction of bioactive compounds (Figure 2). The former involves physical operations such as blanching, drying, milling, and sieving, to produce a stable, nutrient-rich powder suitable for direct incorporation into food matrices. The latter employs solvent-based or green extraction techniques to recover bioactive compounds including phenolics, flavonoids, chlorophylls, carotenoids, and proteins with functional and therapeutic properties (Flórez et al. 2022; Muceniece et al. 2025; Dirr and Karslioglu 2024).

2.2 | Blanching

Blanching, an optional step for nettle processing, typically involve short exposure to hot water (90°C–95°C for 1–3 min) or steam (2–5 min) to inactivate oxidative enzymes, eliminate stinging hairs, and enhance color retention, while preparing the leaves for efficient drying and milling (Upton 2013). While optimized blanching times achieve enzyme inactivation with minimal nutrient loss, overexposure can result in leaching of water-soluble vitamins (C, B-complex) and minerals. Adhikari et al. (2016) described a processing protocol involving blanching (1 min at 80°C), cabinet drying at 60°C for 48 h, and subsequent grinding and sieving to obtain nettle leaf powder. Similarly, Rutto et al. (2013) observed that vitamin A, calcium, and iron contents were modestly affected by cooking, whereas sodium remained stable unless salt was added to the cooking medium. The same study noted alterations in the fatty-acid profile, with saturated fatty acids partially converted into mono- and poly-unsaturated forms during heating. Despite these processing-induced losses, blanched nettles retain substantial micro-nutrient density and antioxidant capacity, supporting its role as a fortifying ingredient in composite and functional food formulations.

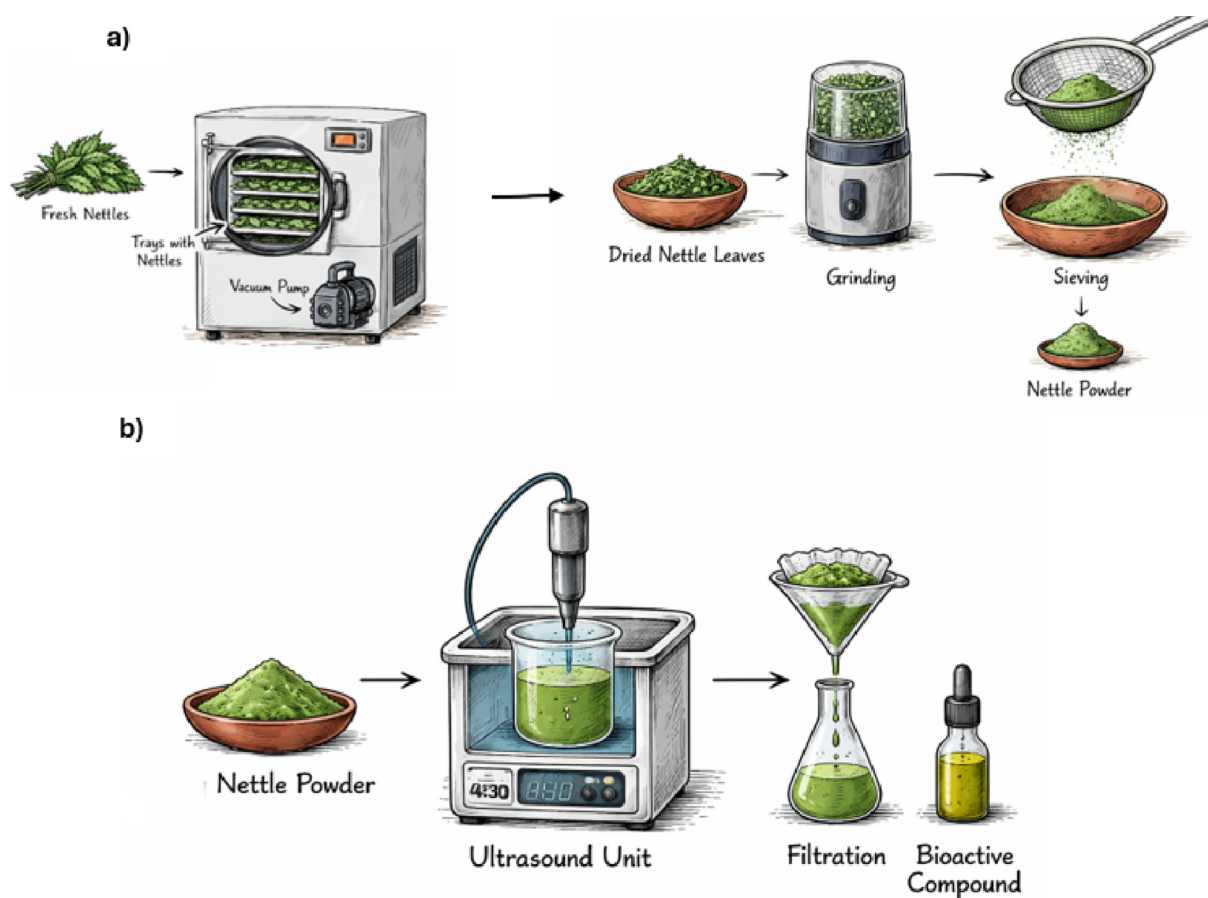


FIGURE 2 | Processing and extraction of nettle. (a) Preparation of nettle leaf powder, involving freeze-drying of fresh nettle leaves, followed by grinding and sieving to obtain a fine, homogeneous powder. (b) Ultrasound-assisted extraction of bioactive compounds from nettle powder, where the powder is dispersed in solvent and subjected to ultrasonic treatment, followed by filtration to yield a liquid bioactive extract.

2.3 | Drying

Effective drying not only stabilizes stinging nettle leaves for long-term storage but also enables their utilization beyond the plant's active growth season (Alibas 2007; Shonte et al. 2020). In Table 1, various drying techniques have been used to obtain nettle leaf powder. Air-drying at temperatures between 50°C and 60°C remain the most used method, providing a balance between process efficiency and nutrient retention (Droštinová et al. 2015). Maintaining the leaves in shaded, and aerated conditions has been shown to retain chlorophylls, carotenoids, and vitamin C more effectively (Maietti et al. 2021). However, prolonged air-drying may lead to quality deterioration, including color changes and losses of ascorbic acid and carotenoids. Another method, oven-drying, was also found to be effective; however, it lead to some nutrient losses. For instance, while Droštinová et al. (2015) recorded 1.53 mg/g carotenoids in oven-dried nettle leaves, Adhikari et al. (2016) reported higher levels (3.5 mg/g).

To improve energy efficiency and bioactive compound preservation, recent advances include freeze-drying (Figure 2), microwave-assisted, and solar drying techniques (Table 2). Freeze-drying, although energy-intensive, produces powders with superior color retention, rehydration capacity, and phytochemical stability, preserving sensitive bioactives such as chlorophylls, carotenoids, and phenolic compounds. Chakravartula et al. (2021) compared convective and freeze-drying of both blanched and unblanched nettle leaves, reporting significant differences in moisture, color, flow properties, pigments, and phenolic retention. In most experiments, oven-dried and freeze-dried nettle leaves showed stronger antioxidant activity, with

DPPH and FRAP values ranging between 66.3% and 81.57% and 42.82%, respectively (Adhikari et al. 2016; Sahal et al. 2025; Tarasevičienė et al. 2023). Kukric et al. (2012) recorded lower FRAP (7.50 mM Fe(II)/g), DPPH (31.38 µg/mL), and ABTS (23.55 µg/mL) IC₅₀ values, indicating moderate to high antioxidant potency. These variations are largely attributed to the leaf harvest time, plant genotype, soil composition, and climatic conditions, which significantly influence phenolic biosynthesis (Otlés and Yalcin 2012). Although blanching and thermal drying can reduce ascorbic acid and certain minerals through leaching or oxidation, freeze-drying and shade-drying preserved a greater proportion of heat-sensitive vitamins and pigment-associated micronutrients, preferred for high-value functional foods.

2.4 | Milling and Sieving

After drying, milling and sieving determine the particle size distribution, bulk density, and extraction yields of the flour (Adhikari et al. 2016; Tanyitiku and Njombissie Petcheu 2025). Milling induces structural modifications that enhance mineral extractability and phenolic bioavailability, thus improving nutritional and functional performance (Paulauskienė et al. 2021). Kronbauer et al. (2023) observed that ground nettle leaves (< 1 mm) produced significantly higher extraction yields than coarser fractions (1–3 mm). On the other hand, coarser fractions tend to retain more insoluble fiber, contributing to improved water absorption capacity and textural attributes in composite food formulations such as breads, pasta, and extruded products (Kronbauer et al. 2023; Tanyitiku and Njombissie Petcheu 2025). However, excessive mechanical or thermal stress during milling

TABLE 1 | Amino acid profile of nettle leaf powder.

Amino acids		Rutto et al. (2013) (g/100 g)	Sahal et al. (2025) (%)
Essential amino acid	Histidine (His, H)	0.53 ± 0.11	—
	Isoleucine (Ile, L)	1.13 ± 0.20	—
	Leucine (Leu, L)	2.09 ± 0.033	3.138
	Lysine (Lys, K)	1.37 ± 0.11	0.984
	Methionine (Met, M)	0.31 ± 0.04	—
	Phenylalanine (Phe, F)	1.27 ± 0.17	0.896
	Threonine (Thr, T)	1.08 ± 0.05	—
	Valine (Val, V)	1.40 ± 0.23	0.171
	Cysteine (Cys, C)	—	14.396
	Tryptophan (Trp, W)	—	0.533
Non-essential amino acid	Tyrosine (Tyr, Y)	0.95 ± 0.13	0.416
	Arginine (Arg, R)	1.57 ± 0.27	0.666
	Aspartic acid (Asp, D) + asparagine (Asn, N)	1.01 ± 0.25	4.257 (Aspartic acid) + 1.359 (asparagine)
	Glutamic acid (Glu, E) + glutamine (Gln, Q)	2.13 ± 0.19	15.397 (glutamic acid)
	Serine (Ser, S)	1.06 ± 0.15	—
	Proline (Pro, P)	1.11 ± 0.17	—
	Glycine (Gly, G)	1.13 ± 0.16	0.469
	Alanine (Ala, A)	1.40 ± 0.13	2.484
	DOPA	—	2.077

TABLE 2 | Drying methods of nettle leaves and its effect on product quality.

Drying method	Conditions	Effect on product quality	Reference
Oven, freeze drying	Oven (70°C, 15 h), freeze (−40°C, 5 days) drying	Loss of β-carotene and ascorbic acid during oven and freeze drying at 90% and 72%, respectively. Increase phenolic content and antioxidant activity in oven dried leaves.	Shonte et al. (2020)
Oven, microwave, and air drying	Oven (25°C, 65 h), microwave (800 W, 45 s), and air (25°C, 65 h) drying	High Chl a and carotenoids in air (8.15 mg/g, 1.83 mg/g) than oven (7.04 mg/g, 1.53 mg/g) microwave (6.65 mg/g, 1.68 mg/g) drying, respectively.	Droštinová et al. (2015)
Oven, freeze-drying	Oven (40°C, 12–14 h, 1 m/s air flow), freeze (−48 to −55°C, 28 h) drying	High antioxidant, pigments, and color retention in freeze drying	Chakravartula et al. (2021)
Oven, microwave, air, solar, and freeze-drying	Oven (25°C, 65 h), microwave (800 W, 45 s), air (room temperature, 65 h), solar (500 W, 7 h, 35°C in the dark), and freeze (0.133 mBar, −72°C, 17 h) drying	High DPPH, Chl a, Chl b, and total carotenoids in freeze-drying	Branisa et al. (2017)
Microwave, vacuum, oven drying	Microwave (500, 650, 750, 850 W, 4–6 min), air (50, 75, 100, 125°C, 30–120 min), vacuum (20, 50 mm [Hg], 35–65 min), and oven (50, 75°C) drying	Improve leaf color and energy consumption	Alibas (2007)

can lead to protein unfolding, pigment oxidation, and vitamin degradation, thereby negatively affecting the color and nutritional quality of nettle leaf powder (Chakravartula et al. 2021).

2.5 | Packaging and Storage

Proper packaging and storage are essential for preserving the nutritional and functional quality of nettle leaf powder, owing to its highly hygroscopic and light-sensitive characteristics. It should be packaged in moisture-proof, oxygen-impermeable, and opaque materials, to prevent moisture absorption, pigment photodegradation, and oxidative rancidity (Upton 2013; Paulauskienė et al. 2021). Vacuum or nitrogen-flushed packaging has been shown to extend the stability of nettle leaf powders by limiting lipid peroxidation and enzymatic browning (Droštinová et al. 2015). The shelf-life stability of nettle powder depends primarily on optimal storage conditions that include ambient temperature ($\leq 25^{\circ}\text{C}$) and relative humidity (below 60%), as higher humidity accelerates caking, microbial growth, and chlorophyll degradation (Rutto et al. 2013; Shonte et al. 2020).

2.6 | Extraction of Nettle Bioactive Compounds

Nettles contain a broad spectrum of secondary metabolites such as phenolic acids, flavonoids, carotenoids, chlorophylls, and bioactive peptides (Dirr and Karslioglu 2024; Flórez et al. 2022; Tarasevičienė et al. 2023). While phenolic compounds typically occur as esters or glycosides, flavonoids are primarily present as glycosidic conjugates, making extraction a key determinant of yield, stability, and bioactivity (Proestos et al. 2006).

Traditionally, solvent extraction, most often with water or hydroalcoholic mixtures, has been employed to recover nettle hydrophilic and lipophilic bioactive compounds (Table 3). Total phenolic contents (TPC) range between 75.08 and 128.75 mg

gallic acid equivalents (GAE)/g dry weight, whereas total flavonoid contents (TFC) were reported at 43.91 ± 0.41 mg quercetin equivalents (QE)/g (Table 4). Muceniece et al. (2025) reported that the extraction of 5 g of dry leaf powder in 100 mL water yielded between 4.2 and 5.1 mg GAE/g total phenolics. Ghaima et al. (2013) reported higher TPC in nettles (48.3 mg GAE/g) than in dandelion (10.2 mg GAE/g). In comparative studies, Elez Garofulić et al. (2021) recorded higher TPC values (359.51 ± 14.58 to 2368.89 ± 30.11 mg GAE/100 g), which was depended on the extraction technique and solvent used, while Otles and Yalcin (2012) reported wide variability in TPC (151–1941 mg GAE/g) from different Turkish coastal regions. Flórez et al. (2022) used modeling to predict optimal water extraction conditions, and 3.15 h yielded 10–27 mg GAE/g total phenolics. Extraction efficiency depends strongly on temperature, solvent polarity, and solid-to-solvent ratio, with optimal recovery generally achieved at 40°C – 60°C for 30–90 min under moderate agitation (Gülçin et al. 2004; Muceniece et al. 2025).

Moreover, recent advances have focused on green extraction technologies—including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pulsed electric fields (PEF), high-pressure processing (HPP), enzymatic extraction, and supercritical fluid extraction (SFE)—that enhance efficiency and sustainability (Đurović et al. 2022; Kagula et al. 2026; Zeković et al. 2017). For instance, Tarasevičienė et al. (2023) used UAE at 70°C for 40 min to obtain 15.3 mg GAE/g polyphenols. Đurović et al. (2022) employed supercritical CO_2 extraction to recover chlorophylls (33.00–7365.11 mg/100 g) and carotenoids (166.88–722.62 mg/100 g). In the same study, main fatty acids obtained included α-linolenic (31.06–58.42 mg/g), palmitic (9.17–13.12 mg/g), and linoleic (10.93–16.51 mg/g) acids. Although supercritical fluid extraction (SFE) is highly effective for the recovery of lipophilic compounds, the exhausted plant material remains a valuable source of bioactive

TABLE 3 | Extraction of nettle bioactive compounds.

Extraction method (s)	Conditions	Components examined	References
HPH and PEF	For HPH, thawed extract was homogenized in 3 cycles at 300–600 bars at < 40°C to reach a particle size distribution of 90–150 µm. For PEF, samples were treated to a specific energy of 20 kJ/kg and an electric field strength of 3 kV/cm. The system supplied high-voltage exponential decay, monopolar pulses with an interval of 0.5 s (2 Hz), and pulse duration of 40 µs.	Protein, chlorophyll	Dirr and Karslioglu (2024)
PEF	Temperature (30°C–70°C), specific energy (0–30 kJ/kg). High-voltage exponential decay pulses (7, 15, and 22), monopolar pulses of 0.5 s (2 Hz) interval, 40 µs pulse duration, and 3 kV/cm electric field strength	Soluble protein	Kronbauer et al. (2023)
PEF	Proteolytic enzyme treatments, fermentation (<i>Fusarium</i> spp.)	Protein	Dirr and Özmütlu Karslioglu (2023)
Solid liquid	Extraction in phosphate citrate buffer at pH = 3, 3.5, 4, 4.5, 5, 5.5, 6, and 6.5, then centrifuged at 8000 g for 10 min at 4°C	Protease	Bouassida et al. (2017)
Acetyl chloride/methanol	Blending in acetone, shaking with diethyl ether and water, and drying over anhydrous sodium sulfate	Fatty acid, carotenoids	Guil-Guerrero et al. (2003)
Solid–liquid extraction (soxtherm)	Soxtherm extraction was carried out at 150°C under reduced pressure for 2 h using petroleum ether as solvent. Lipids extracted using the soxtherm method were converted to fatty acid methyl esters (FAMES) through alkaline and acidic methanolysis, followed by hexane extraction and dilution prior to chromatographic determination of fatty acid composition.	Saturated and unsaturated fatty acids	Đurović et al. (2018)
80% methanol–water mixture	10 mL extraction liquid was added into 1 g of the sample and extracted for 1 h at 50°C in closed vessels	Phenolic profile	Otles and Yalcin (2012)
Ultrasound	Ultrasonic bath (with and without stirring) with orbital shaker at 150 rpm, 65°C for up to 4 h.	TPC, DPPH, and ABTS	Flórez et al. (2022)
Solid liquid	Maceration using water, ethanol (50, 70, and 96%), and methanol (50, 70, and 96%), at 4°C in the dark for 72 h.	TPC, DPPH, and TFC	Tarasevičienė et al. (2023)
MAE, PLE, and CE	Variant extraction temperature (40, 60, and 80°C), irradiation time (5, 10 min) and microwave power (300, 600 W) in three different solvents, water, 30% aqueous ethanol and 30% aqueous acetone.	TPC	Elez Garofulić et al. (2021)
Sonication, Maceration	Sonication at 100 W/g, temperature < 40°C. Maceration in a dark glass container in a dark room at room temperature for 30 days	Polyphenol yield, AGE inhibition, vitamins, and minerals	Muceniece et al. (2025)
SFE	Supercritical CO ₂ under three pressures (100, 200, and 300 bar), two temperature	Chlorophylls and carotenoids	Đurović et al. (2022)

(Continues)

TABLE 3 | (Continued)

Extraction method (s)	Conditions	Components examined	References
SWE, UAE, and MAE	levels (40, 60°C), at 0.2 kg/h CO ₂ rate flow for 5 h UAE included sonication for 30 min at 156 W. MAE included microwave power of 450 W for 30 min. For SWE, pressure was maintained with nitrogen at 35 bar, temperature 125°C with the heating rate of 10°C/min using a heating plate at 30 min extraction time.	Total phenolics and flavonoids	Zeković et al. (2017)
UAE, MAE after supercritical fluid extraction	UAE extraction was carried out using ultrasonic power of 156 W, whereas MAE used a microwave power of 450 W. Both experiments ran for 30 min using 5 g of sample in 150 mL of water (solvent-to-sample ratio 30:1).	TPC, flavonoids, DPPH, polyphenolic profile, and cytotoxic activity	Đurović, Pezo, et al. (2023)

Abbreviations: AGE, advanced glycation end-product; CE, conventional heat-reflux extraction; HPH, High pressure homogenization; MAE, microwave-assisted extraction; PEF, pulsed-electric fields; PLE, pressurized liquid extraction; SFE, supercritical fluid extraction; SWE, subcritical water extraction; UAE, ultrasound-assisted extraction.

TABLE 4 | Bioactive composition of nettle leaves.

Properties	Alemayehu et al. (2016)	Adhikari et al. (2016)	Sahal et al. (2025)
Chemical			
Ash (%)	19.7	16.21 ± 0.54	17.75 ± 1.59
Moisture (%)	8.8	7.04 ± 0.77	8.14 ± 0.40
Protein (%)	21.4	33.77 ± 0.35	26.06 ± 0.48
Carbohydrate (%)	36	37.39 ± 0.72	33.08 ± 2.41
Fats (%)	4.4	3.55 ± 0.06	9.1 ± 0.60
Fiber (%)	9.7	9.08 ± 0.14	5.85 ± 0.13
Calories, total (kcal/100 g)	269.2	307.24 ± 0.13	318.49 ± 2.27
TPC and antioxidants			
Total phenolic content (mg GAE/g)	—	128.75 ± 0.21	75.08 ± 0.26
Total flavonoid content (mg QE/g)	—	—	43.91 ± 0.41
DPPH (%)	—	66.3 ± 0.12	81.57 ± 0.36
FRAP (%)	—	—	42.82 ± 1.32
Carotenoids	—	3496.67 ± 0.56	—
Minerals			
Calcium (mg/100 g)	813	168.77 ± 1.47	35,280 ± 0.014
Iron (mg/100 g)	34.3	227.89 ± 0.21	196.722 ± 0.021
Zinc (mg/100 g)	1.3	—	28.7550 ± 0.013
Magnesium (mg/L)	—	—	1681.351 ± 0.027
Copper (mg/L)	—	—	3.482 0.012

constituents. Đurović, Pezo, et al. (2023) demonstrated that residual stinging nettle biomass retained substantial quantities of phenolic compounds, flavonoids, and antioxidant activity, which could be further recovered using conventional and advanced extraction techniques. These findings highlight the potential of sequential extraction approaches to maximize the utilization of nettle biomass, supporting sustainable processing

strategies and the development of value-added functional ingredients.

Beyond phenolics, protein extraction from nettle leaves has gained growing interest (Table 5). Using high-pressure homogenization combined with isoelectric precipitation, Dirr and Karslioglu (2024) recovered 11.6% of nettle protein. Kronbauer

TABLE 5 | Phenolic compounds of nettle leaves.

Compounds	Zeković et al. (2017) (mg/g)	Orčić et al. (2014) (mg/g)	Zenão et al. (2017) (μg/g)
Phenolic acids			
5-O-Caffeoylquinic acid	ND	1.23–28	71.49 ± 1.70
Caffeic acid	ND	0.21–0.93	163.01 ± 3.63
Ferulic acid	0.010–0.0210	0.009–0.052	—
<i>p</i> -Hydroxybenzoic acid	0.010–0.0486	0.0151–0.037	—
Syringic acid	0.007–0.0202	—	—
Gentisic acid	—	0.0034–0.0082	—
Protocatechuic acid	ND	0.048–0.16	5.90 ± 0.90
Vanillic acid	ND	ND	—
Gallic acid	—	—	—
Quinic acid	—	0.30–0.66	—
<i>p</i> -Coumaric acid	0.004–0.0231	0.026	10.55 ± 0.82
Sinapic acid	0.018–0.0631	—	—
Flavonoids			
Kaempferol	0.009–0.0325	ND	—
Kaempferol-3-O-glucoside	—	0.070	—
Quercetin-3-O-glucoside	0.025–0.095	0.0024–1.08	30.2 ± 0.56
Quercetin	—	—	35.67 ± 0.80
Rutin	0.215–0.722	0.00182–4.6	106.01 ± 2.50
Scopoletin	—	0.012–0.073	—
Esculetin	—	0.0074–0.0125	—
Apigenin	0.010–0.046	—	—
Apigenin glycoside	0.009–0.026	—	—
Rosmarinic acid	0.006–0.013	—	—
Luteolin	0.003–0.011	—	—
Naringenin	0.004–0.021	—	—

Abbreviations: “—”, not mentioned; ND, Not detected.

et al. (2023) extracted 68% of nettle protein within 10 min at 70°C. The authors further showed that PEF pretreatment significantly enhances extraction kinetics as PEF treatment (20 kJ/kg) yielded more protein (22.0 g/100 g) than without PEF (17.8 g/100 g)—a 15% yield increase attributed to greater cell wall disruption and enhanced solvent access (Kronbauer et al. 2023).

Pretreatments such as blanching, ethanol washing, and mild enzymatic hydrolysis have been proposed to minimize protein–polyphenol interactions and improve protein solubility and recovery (Dirr and Karslioglu 2024). Though quantitative comparative data remain limited, current evidence confirms that extraction method, pH, and cell-disruption intensity strongly affect yield, purity, and functional integrity of nettle-derived compounds. For example, Muceniece et al. (2025) demonstrated that maceration and sonication yielded varying microelement profiles in nettle leaf powders, macerated samples being rich in Fe, Sr, Mn, W, Zn, and Ba, while sonicated extracts showed higher levels of Rb and Ni, with both methods confirming iron as the most abundant element (up to 3726 ± 12 μg/g).

These variations in nettle minerals were found to largely depend on leaf harvest period, extraction methods, and environmental factors that affect mineral solubility, retention, and interactions within the plant matrices (Paulauskienė et al. 2021; Sahal et al. 2025). As such, optimized sustainable extraction protocols are therefore crucial for maximizing bioactive recovery and stability in functional food applications.

3 | Bioactive Composition of Processed Nettle Leaves

The nutritional and phytochemical composition of *Urtica dioica* L. leaves contributes to their potential as a functional food ingredient. In addition to protein, dietary fiber, vitamins, and minerals, nettle leaves contain diverse bioactive compounds, including phenolic acids, flavonoids, carotenoids, chlorophylls, phytosterols, and polysaccharides. These constituents have been associated with various biological activities, including antioxidant, anti-inflammatory, antimicrobial, anti-diabetic, and immunomodulatory effects. Consequently, nettle leaves may have potential health-related applications through

mechanisms involving oxidative-stress regulation, glucose and lipid metabolism, inflammatory responses, and immune function (Figure 3).

3.1 | Proteins

Proteins are key nutritional and functional components of *Urtica dioica*, of which 70% are digestible (Zhang et al. 2023).

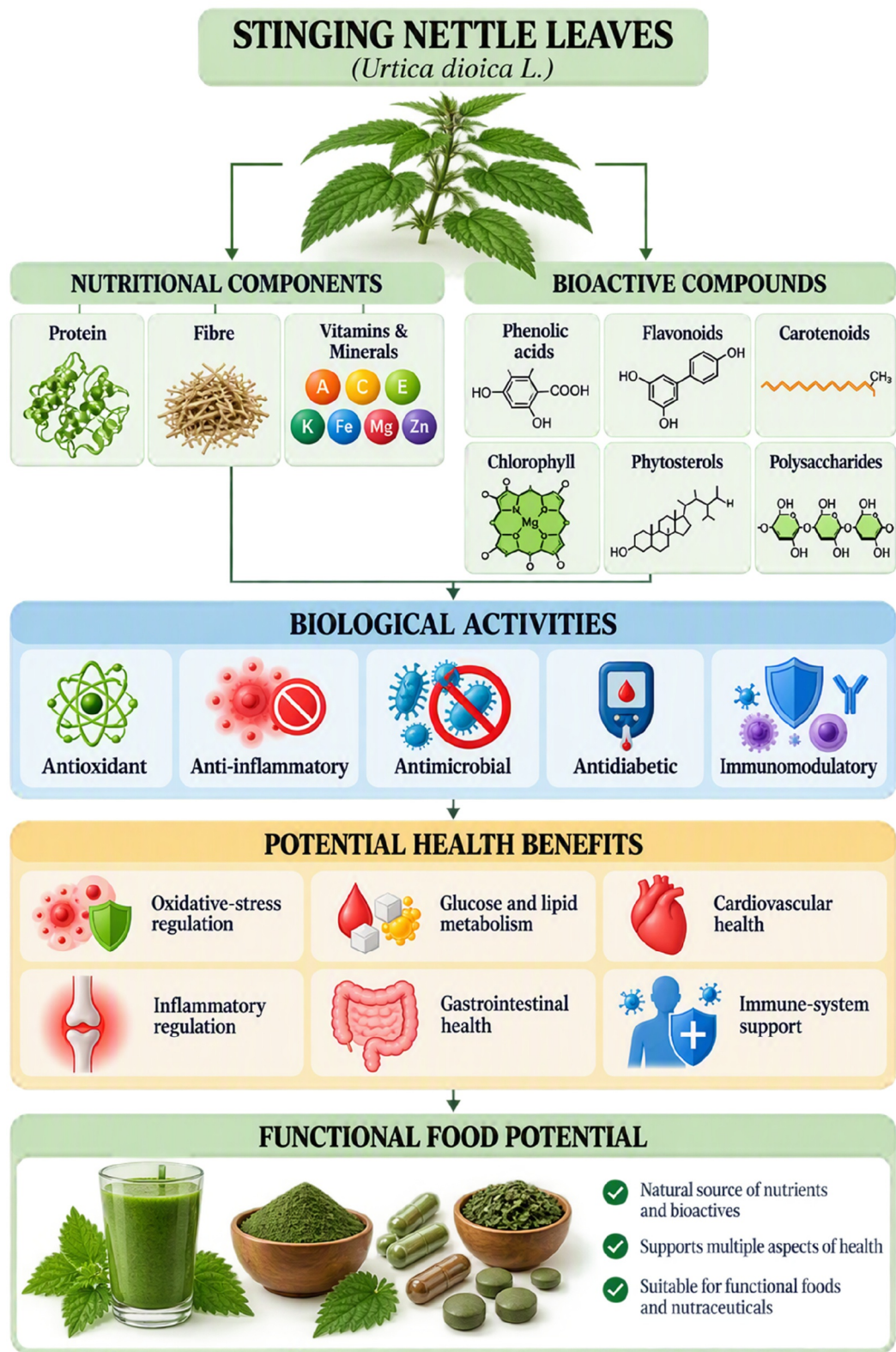


FIGURE 3 | Conceptual relationship between the major nutritional components and bioactive compounds of stinging nettle (*Urtica dioica* L.) leaves, their reported biological activities, and potential health implications relevant to functional-food applications.

The protein content of nettle leaf powder ranges between 21.40% and 33.77% (dry weight) (Table 4). According to Shonte et al. (2020), *Urtica dioica* contains higher protein levels (26.0%) than several common leafy vegetables, including spinach (*Spinacia oleracea*, 25.6%), alfalfa (*Medicago sativa*, 26.1%), and ora-pro-nobis (*Pereskia aculeata*, 28.4%). While Adhikari et al. (2016) reported that nettle proteins (33.77%) are considerably higher than that of wheat (10.6%) and barley (11.8%), Alemayehu et al. (2016) reported nettle proteins of 21.40%, that are comparable to chickpea (20.23%–21.07%) and haricot bean (17.95%–21.95%) but higher than carrot (3.57%–5.68%), orange fleshed sweet potato (4.6%), maize (9.01%), and anchote (3.91%–6.44%). Nettle leaf proteins are characterized by a well-balanced amino acid composition (Table 1), containing 18 different amino acids with 16 in free form (Bhusal et al. 2022; Zhang et al. 2023). They are particularly high in lysine, leucine, isoleucine, threonine, valine, arginine, glutamic acid, glutamine, and alanine, and were found to be better than almond (dry) and comparable to common bean (*Phaseolus vulgaris*) and chicken (*Gallus gallus*) (Rutto et al. 2013). This richness in proteins and associated amino acids can nutritionally enhance nettle incorporated foods, and thus serve as a protein-rich supplement in starchy diets, particularly among poor and undernourished populations (Dirr and Karslioglu 2024; Dirr and Özmutlu Karslioglu 2023; Rutto et al. 2013).

Additionally, in vitro and in vivo studies indicate that bioactive peptides derived from nettle proteins contribute to antioxidant, anti-inflammatory, antiviral, and antihypertensive activities, largely mediated by their ability to inhibit angiotensin-converting enzyme (ACE) and modulate oxidative stress pathways (Ahangarpour et al. 2012; Chehri et al. 2022; Dirr and Karslioglu 2024; Zahra Sadat et al. 2021). For instance, *Urtica dioica* agglutinin (UDA), a single-chain polypeptide composed of 11 exogenous lectins and 89 amino acids, was found to possess red blood cell adhesion capabilities (Bhusal et al. 2022). It also prevent arachidonic acid metabolism in viruses and cause T-lymphocytes to create cells in a particular manner that enhance immunity (Zhang et al. 2023). However, the reported effects depend on the composition of the plant material, processing conditions, extract concentration, and experimental model, and further human studies are required to establish specific health effects.

3.2 | Dietary Fiber

Dietary fiber represents the indigestible portion of plant material that play a vital role in processes such as maintaining gastrointestinal health, moderating glycemic responses, and supporting lipid metabolism (Shaikh 2022; Toplicean et al. 2024). Nettle leaves are recognized for their high dietary fiber content, which significantly contributes to their functionality in food formulations (Sahal et al. 2025; Rutto et al. 2013). Its fiber content ranges between 5.86% and 9.70% (Table 4), primarily cellulose (80%–90%), hemicellulose (15%–20%), and lignin (5%–10%), which together contribute to the plant's high tensile strength and characteristic lightweight hollow structure (Adhikari et al. 2016; Rutto et al. 2013; Sahal et al. 2025). This insoluble fiber also confers high water-binding and bulking capacity, whereas the soluble fraction (representing 10%–15% of total fiber) provides cholesterol-lowering, prebiotic, and

viscosity-modifying properties (Gülçin et al. 2004; Shaikh 2022; Tanyitiku and Njombissie Petchu 2025). Nettle fiber contributes to slowing glucose absorption and promote satiety, as well as enhances bowel regularity and reduce the risk of colorectal cancer (Paulauskienė et al. 2021; Shaikh 2022; Tanyitiku et al. 2024). However, high fiber inclusion in nettle-incorporated bread was found to increase mixing torque, reduce specific loaf volume, and modify crumb texture during baking; this necessitates a controlled incorporation and possible combination with hydrocolloids or enzymes to balance food structure and palatability (Đurović et al. 2020; Wójcik et al. 2021).

3.3 | Chlorophylls and Carotenoids

Chlorophylls and carotenoids form the principal class of photosynthetic pigments in nettle leaves that not only impart their characteristic deep green coloration but also contribute significantly to the plant's nutritional, bioactive, and functional properties (Maietti et al. 2021). Nettle leaves are particularly rich in chlorophylls a and b, with reported concentrations ranging from 0.698 to 0.882 mg/g and 0.285 to 0.320 mg/g dry weight, respectively, making them one of the most chlorophyll-dense leafy plants (Kukric et al. 2012). Similarly, nettle leaf carotenoids vary between 5.14 and 7.48 mg/100 g dry weight and 21.6 and 32.3 mg/100 g fresh weight (Kukric et al. 2012; Paulauskienė et al. 2021). Đurović et al. (2017) reported higher chlorophylls and carotenoids contents of 304.63 mg/100 g and 69.07 mg/100 g, respectively. Guil-Guerrero et al. (2003) identified nine major carotenoids in nettle leaves, including lutein, β -carotene, and their isomers. Both chlorophylls and carotenoids function as bioactive and technological agents. They are widely used as natural colorants, antioxidants, and stabilizing compounds in functional food formulations (Guil-Guerrero et al. 2003; Kukric et al. 2012). Specifically, while carotenoids, particularly β -carotene and lutein, act as potent antioxidants that scavenge reactive oxygen species, protect cellular membranes from oxidative stress, and support visual and immune health (Droštinová et al. 2015; Flórez et al. 2022; Guil-Guerrero et al. 2003), nettle chlorophylls are associated with detoxification and anti-carcinogenic effects, attributed to their ability to bind aflatoxins and modulate oxidative stress pathways (Maietti et al. 2021; Zeković et al. 2017). In addition to these physiological roles, nettle chlorophylls are utilized commercially as natural green colorants (E140) in vegetable powders, concentrates, bakery products, and herbal preparations (Arfa and Hassan 2023; Đurović et al. 2018; Guil-Guerrero et al. 2003; Sahal et al. 2025). The abundance of these pigments makes nettle leaf flour a dual-purpose ingredient, contributing both bioactive functionality and natural color enhancement in clean-label and sustainable food formulations (Kukric et al. 2012; Tanyitiku and Njombissie Petchu 2025).

3.4 | Carbohydrates

Carbohydrates remain a primary energy source in human nutrition. In Table 4, nettle carbohydrate ranges between 33.08% and 37.39%, which is lower when compared to wheat (86.5%) and barley flour (81.8%) (Adhikari et al. 2016). Unlike cereal-based flours, where carbohydrates are primarily starch, nettle carbohydrates are dominated by non-starch polysaccharides, including celluloses, hemicelluloses, pectins, and minor soluble

sugars (Sahal et al. 2025). They constitute an important macronutrient of nettle leaves, serving not only as an energy source (contributing 269.2–318.14 kcal/100 g) but also a reservoir of structural, textural and functional polysaccharides (Adhikari et al. 2016; Tanyitiku and Njombissie Petcheu 2023). They form complex matrices with polyphenols, proteins, and minerals, influencing extractability and digestibility. In terms of simple sugars, nettle leaves contain small amounts of glucose, fructose, and sucrose, typically less than 5% of dry weight. These naturally occurring sugars contribute less to high glycemic load, thus making nettle flour desirable for glycemic control and digestive health (Zahra Sadat et al. 2021).

In addition, nettle leaves were reported to possess insulin-mimetic, insulin-sensitizing, and secretagogue properties, where they form unique glucose-permeable pores in lipid bilayers, activate peroxisome proliferator-activated receptor- γ , and modulate the translocation of glucose transporter-4 from the cytoplasm to the skeletal muscle (Chehri et al. 2022; Di Virgilio et al. 2015; Zhang et al. 2023).

3.5 | Fats

The total fat content of nettle leaves ranges between 3.55% and 9.1% (Table 4). Although not considered an oilseed plant, nettles contain notable amounts of beneficial lipids, particularly unsaturated fatty acids of nutritional and physiological relevance (Rutto et al. 2013). The most abundant fatty acids were lauric acid (C12:0), palmitic acid (C16:0), and oleic acid (C18:1), representing 20.94% (348.07 mg/g), 18.57% (309.06 mg/g), and 13.16% (219.44 mg/g) of the total fatty acid content, respectively. In contrast, heptadecenoic acid (C17:1) was present at the lowest concentration, accounting for only 0.13% (2.20 mg/g) (Đurović et al. 2018; Tarasevičienė et al. 2023). Guil-Guerrero et al. (2003) reported differences in C16:0, C18:2, and C18:3 fatty acids in mature (17.9%, 11.6%, and 40.7%) and young nettle leaves (20.1%, 18.1%, and 29.6%), respectively. Similarly, Đurović et al. (2017) reported that α -linolenic acid (C18:3), palmitic acid (C16:0), and linoleic acid (C18:2) were the predominant fatty acids in stinging nettle leaves, occurring at concentrations of 67.98, 60.97, and 55.99 mg/g, respectively. Among the terpenes identified, linalool was the most abundant compound (5.1 mg/g), whereas iron was the dominant trace element, with a concentration of 150.97 mg/g. While these lipid fractions could contribute to emulsification, flavor retention, and mouthfeel enhancement in bakery products, the fatty acids n-3, n-6 and PUFAs were reported to possess anti-inflammatory, vasodilatory, antithrombotic, and hypolipidemic properties (Flórez et al. 2022; Igual et al. 2022; Nassiri-Asl et al. 2009; Tanyitiku et al. 2024).

3.6 | Micronutrients

Nettles are vital sources of micronutrients that support numerous metabolic and physiological activities in humans. Its ash content varies between 16.21% and 19.70% (Table 4), with minerals accounting for approximately 20% of nettle dry mass (Adhikari et al. 2016; Bhusal et al. 2022). According to Sahal et al. (2025), nettle leaf flour contains high levels of calcium (35,280 mg/100 g), magnesium (1681 mg/L), iron (196.7 mg/100 g), copper (3.5 mg/L), and zinc (28.8 mg/100 g). In comparison,

Adhikari et al. (2016) found higher iron (227.89 mg/100 g), and Paulauskienė et al. (2021) reported higher copper levels (10.2–18.4 mg/kg). Furthermore, nettle leaves are rich in both water-soluble (vitamins C and B-complex) and fat-soluble (vitamins A, D, E, and K) compounds, providing substantial levels of β -carotene, α -tocopherol, and folate (Rutto et al. 2013; Paulauskienė et al. 2021). Rutto et al. (2013) reported that processed nettle can supply up to 90%–100% of the recommended daily intake of vitamin A (as β -carotene). Analysis of stinging nettle leaf extracts revealed vitamin C concentrations ranging from 6.69 to 74.89 mg/L, vitamin B1 from 3.46 to 6.70 mg/L, vitamin B2 from 16.38 to 89.63 mg/L, vitamin B3 from 28.37 to 197.35 mg/L, and vitamin B6 from 1.22 to 104.15 mg/L, depending on the extraction technique used (Đurović, Micić, et al. 2023). However, Popov et al. (2020) reported that the elemental composition of stinging nettle extracts obtained by Soxhlet extraction (SE), maceration (MAC), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) varied considerably depending on the extraction method and operating conditions. Among the macroelements, the MAE extract exhibited the highest concentrations of potassium (965.60 mg/L) and magnesium (191.99 mg/L), whereas the MAC extract contained the greatest amounts of calcium (464.24 mg/L) and sodium (90.37 mg/L). Greater variability was observed for trace elements, with the UAE extract showing the highest concentrations of iron and zinc, while manganese and nickel were most abundant in the MAE extract. Copper, chromium, and tin also reached their maximum concentrations in the UAE extract. With respect to potentially toxic elements, lead was detected in all extracts, with slightly higher levels in the SE and UAE extracts than in the MAC and MAE extracts. Cadmium was present only at trace levels in the SE and UAE extracts, whereas mercury was not detected in any sample. Arsenic was detected exclusively in the SE extract, which the authors attributed to possible ethanol-related interference during sample introduction into the argon plasma. From a nutrition and functional perspective, this micronutrient density underpins most of nettle's health-promoting effects (Table 6). For instance, they could play critical roles in enzymatic catalysis, redox regulation, and cellular signaling; iron and calcium could contribute to hemoglobin synthesis, oxygen transport, and bone integrity; and bioavailable magnesium and potassium could support neuromuscular and cardiovascular function (Muceniece et al. 2025; Shaikh 2022).

3.7 | Phenolic Acids and Flavonoids

Phenolic acids and flavonoids constitute the principal bioactive compounds in nettle leaves. In Table 5, major phenolic acids include caffeic, chlorogenic, *p*-coumaric, ferulic, and gallic acids, whereas flavonoids consist of quercetin, rutin, kaempferol, and isorhamnetin derivatives. These polyphenols exhibit potent antioxidant and health-promoting properties (Figure 3), largely through modulation of oxidative stress and redox-sensitive signaling pathways (Tola et al. 2025). For instance, in vitro assays showed that these bioactive compounds inhibit α -amylase and α -glucosidase, thereby delaying carbohydrate digestion and attenuating postprandial glucose spikes (Zahra Sadat et al. 2021). Similarly, animal models of diabetes fed nettle-enriched diets exhibit improved glycemic control, reduced HbA1c, and better

TABLE 6 | Mechanisms and associated health benefits of nettle bioactive compounds.

Function	Active component	Proposed mechanisms	Host studied	Key outcomes	Reference
Hepatoprotective	Minerals, water-soluble vitamins, and polyphenols, primarily phenolic acids and rutin.	Possibly multiple mechanisms, primarily involving antioxidant activity	In vitro fatty liver HepG2 cell model	Improve HepG2 cell viability under oxidative stress, reduce lipid accumulation, and enhance mitochondrial oxygen consumption in the fatty acid oxidation pathway at mitochondria complex I.	Muceniece et al. (2025)
	Phenolic compounds, chlorophylls, vitamins A and E	Enhance detoxifying enzymes, lipid peroxidation, DPPH activity (IC ₅₀ 78.99 ± 0.17 µg/mL) and NO (IC ₅₀ 101.39 ± 0.30 µg/mL).	In vivo (CCl ₄ challenged rats)	Increase liver enzymes activity	Joshi et al. (2015)
Antidiabetic	Kaempferol, apigenin, catechin, myricetin, carvacrol, ursolic, scopoletin, chlorogenic acid, β-sitosterol, quercetin, rutin, esculetin, vanillic acid, isorhamnetin, and gentisic acid in 50 (mg/kg/day) of hydroalcoholic extract	Quercetin activates GPx and inhibits hydrogen peroxide (H ₂ O ₂) from oxidative damage. It weakened oxygen-glucose deprivation, free radical, and excitotoxin-induced neurotoxicity, and hindered breaking DNA strands and cytotoxicity. Scopoletin also ameliorates long-term potentiation by increasing neurotransmitters' release of nicotinic acetylcholine receptor (nAChR) and promoting neural plasticity in the hippocampus and ultimately improves cognitive impairments.	In vivo (male wistar rat)	Decrease in antioxidant enzymes (GPx, SOD, CAT and GSH), increase in pro-inflammatory cytokines (TNF-α and IL-1β) and lipid peroxidation (MDA) in the hippocampus of STZ-induced diabetic rats.	Rahmati et al. (2021)
	Phenolic compounds	Insulin-enhancing, decrease insulin resistance	In vivo (male sprague-dawley rat)	Decrease blood glucose, cholesterol and triglyceride, CRP inflammatory marker, and increase insulin levels	Zahra Sadat et al. (2021)

(Continues)

TABLE 6 | (Continued)

Function	Active component	Proposed mechanisms	Host studied	Key outcomes	Reference
Antioxidant, hepatoprotective	Phenolic compounds	LDL takes the cholesterol from liver to tissues; HDL facilitates the translocation of cholesterol from the peripheral tissues to the liver for catabolism	In vivo (male wistar rats)	Decrease in serum glucose, insulin, low-density lipoprotein (LDL), leptin, and LDL/HDL ratio and fasting insulin resistance index	Ahangarpour et al. (2012)
	—	Insulin secretagogue, PPARgamma agonistic, and alpha-glucosidase inhibitory effects	In vivo (46 patients)	Lower blood fasting glucose in advanced type 2 diabetes mellitus, 2 h postprandial glucose	Kianbakht et al. (2013)
	Phenolic acids (caffeic, ferulic, chlorogenic), flavonoids (quercetin, kaempferol), chlorophylls, and carotenoids	Radical scavenging (DPPH, ABTS) due to hydrogen donating ability, chelation of ferrous ions	In vitro and in vivo (albino sprague-dawley male rat model)	Inhibition of peroxidation in linoleic and acid emulsion of 50, 100, and 250 µg of extract was 39%, 66%, and 98%, respectively, and greater than that of 100 µg of 30% α-tocopherol.	Gülçin et al. (2004)
	Antioxidant activity, DPPH radical scavenging activity and nitric oxide scavenging activity	Biotransformation of CCl ₄ by cytochrome P450 enzymes to produce CCl ₃ radical. CCl ₃ radical produces CCl ₃ O ₂ after reacting with oxygen, which then covalently binds with cellular macromolecules and biomembranes to trigger lipid peroxidation.	In vitro, in vivo (rats and Indian adult earthworms (<i>Pheretima posthuma</i>))	Decrease in serum ALT, AST, ALP, total bilirubin, and malonyldehyde (MDA); increase in superoxide dismutase (SOD) level, indicating inhibition of lipid peroxidation and improvement of antioxidant defense enzyme system	Kataki et al. (2012)
Antimicrobial	Flavonoid, glycosides, phenols, alkaloid, tannins, and terpenoids	Lipid peroxidation in the inhibition of linoleic acid emulsion	In vitro	Inhibit <i>A. hydrophila</i> , <i>S. typhi</i> , <i>S. aureus</i> , <i>B. cereus</i> , <i>E. coli</i> with highest inhibition zone (24 mm) with <i>B. cereus</i>	Ghaima et al. (2013)
	TPC, total flavonoids, and flavonols	Enzymatic and moderate non-enzymatic antioxidative action peroxidases and phenols as important part of the antioxidant metabolism	In vitro	MIC and MBC ranged between 9.05 and 149.93 mg/mL, and exhibit weak activity against <i>B. subtilis</i> and <i>E. coli</i>	Kukric et al. (2012)

(Continues)

TABLE 6 | (Continued)

Function	Active component	Proposed mechanisms	Host studied	Key outcomes	Reference
	Phenolic compounds, alkaloids, tannins, and terpenoids	Activity could be due to phenolic compounds and secondary metabolites	In vitro	Gram-positive bacteria were susceptible, while the gram-negative bacterium (<i>E. coli</i>) was resistant. Highest inhibitory effect with 500 mg/ml of extract with <i>S. saprophyticus</i> susceptible at 89%. <i>S. aureus</i> could be used to treat urinary tract infections	Mirtaghi et al. (2016)
	Hydroxycinnamic acids (chlorogenic acid, caffeic acid, rosmarinic acid) and flavonoids (quercetin)	Bacteriostatic effect principally due to the presence of carboxylic acid (COOH), two hydroxyl (OH) groups in the para and ortho positions of the benzene ring and also a methoxyl (OCH ₃) group in the meta position.	In vitro	Susceptibility of methicillin-sensitive and methicillin-resistant <i>S. aureus</i> with inhibition halos varying between 11.3 and 19.3 mm, MIC values ranged between 0.0625 and 0.500 mg/mL.	Zenão et al. (2017)
	Polyphenols, organic acids, and chlorophyll derivatives	Membrane disruption; inhibition of microbial enzymes, chelation of essential metals	In vitro	Inhibition of gram-positive and gram-negative bacteria (<i>E. coli</i> , <i>S. aureus</i>)	Elez Garofulić et al. (2021)
	Polyphenols	Bactericidal and bacteriostatic activity	In vitro	Activity observed against gram-negative <i>P. fragi</i> and <i>C. jejuni</i> with MIC less than 0.512 mg/mL, <i>Shewanella</i> and <i>S. aureus</i> were sensitive. No inhibition against <i>L. innocua</i> , <i>E. coli</i> , <i>C. albicans</i> and <i>P. anomala</i>	Elez Garofulić et al. (2021)
	Phenolic compounds	Inhibit motility, adhesion to polystyrene surfaces, and invasion of host cells by <i>C. jejuni</i> through influencing quorum-sensing	In vitro	Inhibit MNV-1 norovirus at 50% inhibitory concentration (1.45–1.87 mg/mL), activity against <i>C. jejuni</i> at 0.625, 1.25 and 2.5 mg/mL	Aydin et al. (2023)
	Rutin, naringenin, kaempferol, <i>p</i> -coumaric acid, and ferulic acid	No links between phenolic acid and antibacterial activity	In vitro	Activity observed against <i>S. aureus</i> and <i>P. mirabilis</i> (MIC = 9.76 µg/mL)	Zeković et al. (2017)

(Continues)

TABLE 6 | (Continued)

Function	Active component	Proposed mechanisms	Host studied	Key outcomes	Reference
Anti-inflammatory, antidiabetic, antibacterial activity, toxicological	Hydroxycinnamic acid (2-O-caffeoylmalic, chlorogenic acid), flavonoids (rutin, quercetin <i>p</i> -coumaroyl glucoside, isorhamnetin 3-O-rutinoside), anthocyanins (peonidin3-O-rutinoside, rosinidin 3-O-rutinoside), fatty acid esters, and terpenes	Possess insulin-like effect or stimulate the pancreatic β -cells to produce insulin, and interfere with the synthesis or liberation of histamine and PG mediators	In vitro (<i>Artemia salina</i> and wistar rats)	Reduce blood glucose level to 63.26%, exhibit anti-inflammatory activity (48.83% after 3 h), and potent activity against <i>S. aureus</i> , <i>S. flexneri</i> , <i>S. typhi</i> , <i>P. aeruginosa</i> , <i>K. pneumoniae</i> , <i>E. coli</i> and <i>E. faecalis</i> , MIC values ranging from 31.25 to 250 μ g/ML.	Dar et al. (2013)
Anti-inflammatory, antioxidant	Caffeic acid, chlorogenic acid, and caffeoylmalic acid	Strong FRAP, CUPRAC, DPPH, and ABTS activities	In vitro	Reduce interleukin-1 β (IL-1 β) in human colon epithelial and adenocarcinoma cells.	Wójciak et al. (2024)
Hypolipidemic, cardioprotective	PUFA (ω -3, ω -6), phytosterols, and flavonoids	Regulation of lipid metabolism; inhibition of HMG-CoA reductase; reduction of LDL oxidation	In vivo (rat)	Reduced serum cholesterol, TG, LDL; increased HDL	Nassiri-Asl et al. (2009)
Nephroprotective	Flavonoids, minerals (Mg, K), and phenolics	Reduce oxidative renal stress; modulate urea and creatinine levels	In vivo (rats)	Improve renal markers; reduce oxidative burden	Hajhashemi et al. (2020)
Antihypertensive	Alkaloids, tannins, flavonoids, saponins, reducing sugars, cardiac glycosides, steroids, and terpenoids in methanolic crude extract	Activity on both vascular endothelial and smooth muscles to release NO and block Ca ²⁺ .	In vitro and in vivo (rats)	Exhibit l-NAME sensitive endothelium-dependent vasodilator effect, inhibited K ⁺ -induced pre-contractions, exhibited Ca ²⁺ channel blocking activity by shifting Ca ²⁺ response curves to the right.	Qayyum et al. (2016)
Antirheumatic	—	IDS 23 (Rheuma-Hek) inhibited phytohemagglutinin, stimulated production of Th1-specific IL-2 and IFN-gamma in peripheral blood mononuclear cells	In vitro	Inhibit lipopolysaccharide stimulated monocyte cytokine expression, indicating an immunomodulating effect	Klingelhofer et al. (1999)

(Continues)

TABLE 6 | (Continued)

Function	Active component	Proposed mechanisms	Host studied	Key outcomes	Reference
Anti-obesity, metabolic regulation	Fiber-polyphenol matrix and flavonoids	Modulation of lipid digestion, delay gastric emptying, and microbiota modulation	In vivo (C57BL/6J mice)	Reduces adipose tissue, fat accumulation, and weight gain; improves insulin resistance (HOMA-IR index) and changes in metabolic genes expression	Fan et al. (2020)
Anticancer	Rutin (25 mg) and oxylipins (18 mg)	Promote endoplasmic reticulum stress through activation of growth arrest and DNA damage-inducible gene 153 (GADD153) triggering apoptosis	In vitro (bronchial epithelial cells, lung fibroblast)	Inhibit cell proliferation in the selected cells, while no toxic effects were observed in normal lung cells.	D'Abrosca et al. (2019)
Nutritional support	Proteins, minerals, vitamins, and chlorophyll	Enhance nutrient density, immune modulation, and hemoglobin synthesis	Estimate of nutritional attributes	Improve nutrient intake and antioxidant defense in composite diets	Rutto et al. (2013)

lipid profiles (Ahangarpour et al. 2012; Fan et al. 2020; Hajiha-shemi et al. 2020).

Quercetin has been identified as the most abundant flavonoid in nettle leaves and is recognized for its potent free radical-scavenging and anticancer properties (Proestos et al. 2006; Rahmati et al. 2021; Zhang et al. 2023). Mechanistically, quercetin forms resonance-stabilized phenoxyl radicals capable of neutralizing peroxy radicals and mitigating oxidative cellular damage (Zhang et al. 2023). In vivo studies have shown that quercetin supplementation can lower fasting blood glucose, total cholesterol, and insulin resistance, while increasing HDL-cholesterol, plasma adiponectin, and hepatic glutathione peroxidase activity (Chehri et al. 2022; Rahmati et al. 2021). Complementary in vitro studies further demonstrate that quercetin downregulates pro-inflammatory mediators such as NF- κ B and COX-2, inhibits lipid peroxidation, mitigates carbon tetrachloride (CCl₄)-induced hepatic injury, and enhances endogenous antioxidant enzyme activities (Gülçin et al. 2004; Zhang et al. 2023). These combined action of nettle-derived phenolic compounds constitute its health-promoting properties, underscoring nettles as a natural source of bioactive compounds for functional food and nutraceutical applications (Qayyum et al. 2016; Rahmati et al. 2021; Tanyitiku et al. 2024).

3.8 | Other Bioactive Compounds

Stinging nettle leaves also contain a range of secondary metabolites, including organic acids (citric, malic, and oxalic acids), sterols (β -sitosterol, campesterol), terpenoids, and biogenic amines such as histamine, serotonin, and acetylcholine, which are primarily localized in the trichomes (Tola et al. 2025; Paulauskienė et al. 2021). In particular, nettle sterol and terpenoid fractions contribute to the anti-inflammatory and hypocholesterolemic effects, partly through modulation of lipid

metabolism and inhibition of cholesterol absorption (Đurović et al. 2020; Shonte et al. 2020). Organic acids enhance the plant's antioxidant potential and were found to improve mineral solubility and bioavailability through natural chelation mechanisms (Shaikh 2022). Collectively, these bioactive compounds support cardiometabolic health by reducing intestinal cholesterol uptake and lowering low-density lipoprotein (LDL) levels without adversely affecting high-density lipoprotein (HDL) cholesterol concentrations (Ahangarpour et al. 2012; Nassiri-Asl et al. 2009).

4 | Functional Properties of Nettle Leaf Powder

Functional properties of flours refer to the physicochemical and technological characteristics of its major constituents, particularly its proteins, carbohydrates, and dietary fibers, that influence how they behave during food preparation, processing, and storage. Functional behaviors such as water-holding capacity, oil-holding capacity, emulsification, gelation, viscosity enhancement, and swelling ability are especially important, as they affect how nettle leaf powder (NLP) integrates into formulations like baked goods, pasta, beverages, and complementary foods. These properties, presented in Table 7, determine the extent to which NLP contributes to the texture, structure, appearance, stability, and overall sensory quality of food products. NLP demonstrates high water absorption capacity (154%–260%) and oil absorption capacity (89%–294%) (Sahal et al. 2025), suggesting its usefulness in moisture retention and fat binding in baked or plant-based products. When compared to gluten-free rice and corn flours, it also exhibits low swelling capacity, high nitrogen solubility index, and good foaming stability, making it suitable for aerated systems such as batters or gluten-free products. Its foaming capacity (~13.9%) can be improved through enzymatic modification or legume-protein blending, as phenolic-protein complexes may enhance interfacial film stability (Tanyitiku and Njombissie Petchu 2025). Color values reported by Chakravartula

TABLE 7 | Functional properties of nettle leaf powder.

Properties	Tanyitiku and Njombissie Petcheu (2025)	Sahal et al. (2025)	Chakravartula et al. (2021)
Swelling capacity (mL)	2.71 ± 0.43	—	—
Nitrogen solubility index (%)	20.85 ± 0.22	—	—
Water absorption capacity (%)	154 ± 0.88	260.16 ± 0.34	—
Oil absorption capacity (%)	89.55 ± 0.02	294.18 ± 0.14	—
Foam capacity (%)	13.91 ± 2.37	—	—
Foam stability (%)	93.66 ± 0.66	—	—
Dispersibility (%)	72.90 ± 0.08	—	—
Water activity (a_w)	0.31 ± 0.08	0.59 ± 0.08	0.24 ± 0.07–0.51 ± 0.02
Tapped density (g/cm ³)	0.20 ± 0.23	0.4170 ± 0.005	0.35 ± 0.02–0.54 ± 0.02
Bulk density (g/cm ³)	0.16 ± 0.08	0.370 ± 0.0025	0.18 ± 0.01–0.41 ± 0.02
Carr's index (%)	20.05 ± 0.22	11.27 ± 0.041	24.00 ± 1.15–48.00 ± 1.63
Hausner's ratio	1.24 ± 0.10	1.12 ± 0.056	1.30 ± 0.01–1.93 ± 0.05
Angle of repose (°)	32.76 ± 1.40	—	—
Color			
L*	36.52 ± 1.13	55 ± 0.038	40.89 ± 1.13–43.85 ± 2.46
a*	−6.88 ± 0.97	−7.5 ± 0.062	−3.76 ± 0.70 to −7.21 ± 1.82
b*	10.44 ± 0.90	21.3 ± 0.082	16.96 ± 0.91–20.32 ± 0.64
ΔE	7.66 ± 0.63	—	5.61 ± 0.88–9.14 ± 1.46
Chroma	—	22.581 ± 0.056	17.56 ± 0.58–21.46 ± 1.34

et al. (2021) for unblanched freeze-dried powder ($L^* = 46.02$, $a^* = -7.21$, $b^* = 20.85$) and by Sahal et al. (2025) ($L^* = 55$, $a^* = -7.5$, $b^* = 21.3$) confirm the visual impact of pigment concentration. In terms of flowability and bulk properties, Tanyitiku and Njombissie Petcheu (2025) reported Carr's index (20.05%), Hausner's ratio (1.24), and angle of repose (32.8°), indicating fair flow, whereas Sahal et al. (2025) recorded bulk density (0.37 g/cm³) and tapped density (0.42 g/cm³), similar to findings by Chakravartula et al. (2021). These parameters influence handling, packaging, and dispersion performance in formulations. However, functional behavior remains highly dependent on processing conditions, and the standardization of drying and milling protocols is critical to ensure reproducibility and industrial scalability.

5 | Innovative Food Applications

Nettle can serve as a sustainable functional ingredient, offering high nutritional density and diverse phytochemicals in health-oriented foods (Ghaima et al. 2013; Kagula et al. 2026; Mohammadian et al. 2024). Nettle leaves are rich in proteins, dietary fiber, vitamins (A, C, and K), minerals, and phytochemicals such as phenolics and flavonoids. These compounds provide antioxidant, anti-inflammatory, glycemic regulatory, and immune-supporting effects. Processing into powder enables incorporation into functional foods, including bread, pasta, soups, smoothies, infant formulations, and dietary supplements (Figure 4).

5.1 | Bakery Products

In bakery applications, nettle powders and extracts have been increasingly explored as functional ingredients for the

fortification of products such as breads, muffins, cookies, biscuits, cakes, and pasta (Table 8). Its partial substitution (up to 20%) significantly increases protein, fiber, mineral (Fe, Ca, and Mg), and antioxidant contents without compromising dough rheology or consumer acceptability (Đurović et al. 2020; Igual et al. 2022; Maietti et al. 2021; Tanyitiku et al. 2024). For instance, Man et al. (2019) reported an increase protein, ash, and fiber from 11.2 to 29.74, 0.57 to 17.67, and 0.69 to 8.37, respectively, and a decrease in bread specific volume when nettle powder was incorporated at 2%–6%. Kumbaji et al. (2026) reported that partial substitution of cassava flour with nettle leaf powder and watermelon peel powder improved the nutritional quality of gluten-free cassava bread through increased protein, fiber, phenolic compounds, and antioxidant capacity. The composite breads also showed reduced starch hydrolysis and predicted glycemic index. In pasta and noodles, Krawęcka et al. (2021) observed an increase in minerals (Ca, Fe, K, and Mg) in durum wheat pasta with Ca reaching 175.9 mg/100 g: 5.8 times higher than the control as well as high chlorophylls and carotenoids (237.58 µg/g and 13.35 µg/g, respectively). It improved ash content, fiber ratio, and micronutrient density, and reduced glycemic index, were all associated to nettle's high fiber, carotenoid, and polyphenol contents that modulate starch digestibility (Krawęcka et al. 2021; Maietti et al. 2021). When incorporated into cereal-legume weaning foods, NLP enhances nutrient density, increasing total phenolic content and antioxidant capacity, that may help address iron deficiency in infants (Kulaitienė et al. 2021; Tanyitiku and Njombissie Petcheu 2023). Likewise, an increase of nettle and fenugreek seeds in cake was directly associated with increase in ash, fat, and protein and DPPH scavenging and a daily consumption of 2–4 cakes, each one containing 2.5 g nettle leaf was recommended (Ataei Nukabadi et al. 2021). In contrast, when incorporated at

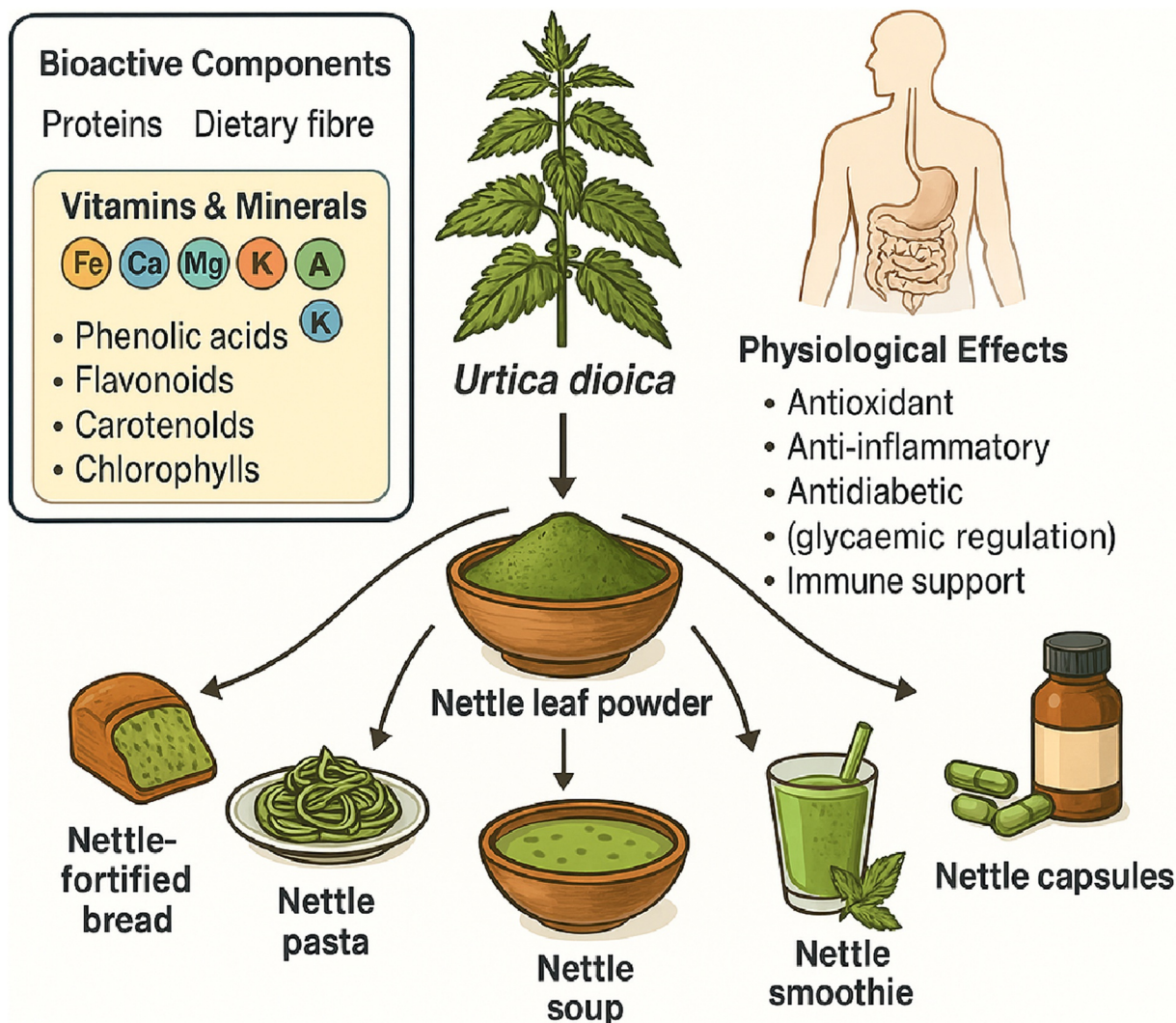


FIGURE 4 | Bioactive components, physiological effects, and food applications of *urtica dioica*.

10%–25% in flatbread, Diddana et al. (2021) reported decrease in protein and fat (11.02–7.21 g and 1.12–0.48 g), increase ash, fiber, and carbohydrate (1.84–3.81 g, 2.19 to 3.05, and 75.53–80.05 g), respectively. Ca, Fe, and Zn contents were five- and twofold higher than that of the control. The high fiber and protein content of nettle contributes to improved nutritional density, whereas its phenolic compounds provide additional antioxidant benefits. Cookies enriched with nettle powder often exhibit elevated total phenolic content and enhanced free radical scavenging activity, commonly measured using assays such as DPPH, ABTS, and FRAP. For example, Tanyitiku et al. (2024) reported an increase in ash (0.32%–2.56%), protein (6.44%–21.52%), total phenolics and antioxidant activity by 27 and seven times, respectively, as well as a decrease in predicted glycemic index (48.60%–33.18%) at up to 20% NLP incorporation in gluten-free corn cookies. These increases in antioxidant activity are largely attributed to the presence of flavonoids, phenolic acids, carotenoids, and chlorophyll derivatives naturally present in nettle leaves. Such antioxidant enrichment may help protect against oxidative stress and contribute to the overall health-promoting properties of fortified bakery products.

In addition to improving antioxidant capacity, the inclusion of nettle powder can influence the carbohydrate digestibility profile of bakery products. Studies have shown that nettle-enriched breads tend to contain higher proportions of slowly digestible starch (SDS) and resistant starch (RS), while reducing rapidly digestible starch (RDS). This shift in starch fractions is associated with a lower predicted glycemic index (GI) compared to conventional wheat bread. In durum wheat pasta at 1%–5%, Krawęcka et al. (2021) reported an increase in TDF from 5.1 g/100 g to 8.82 g/100 g, and in IDF from 2.29 g/100 g to 5.63 g/100 g, with the lowest hydrolysis index (HI = 17.49%) and glycemic index (GI = 49.31%). In terms of nutrient absorption, Marchetti et al. (2018) reported increase bioavailability of lutein and β -carotene, lower carotenoid bioaccessibility than dietary supplement at duodenum and after 48 h of colonic fermentation, maximum bioaccessibility was observed at 24 h of colonic fermentation. Notably, nettle enriched egg pasta demonstrated highest levels for bioaccessibility at 2 h (lower colonic fermentation time) (Marchetti et al. 2018). A lower GI is beneficial for moderating postprandial blood glucose levels, making nettle-fortified bakery products potentially suitable for individuals

TABLE 8 | Innovative application of nettle powder and extract in food products.

Food category	Functional benefits	Key applications
Bakery products	Improved nutritional composition (protein, dietary fiber, and minerals); enhanced antioxidant activity; reduced predicted glycemic index; improved functional properties and extended shelf life	Bread (Đurović et al. 2020; Kumbaji et al. 2026; Maietti et al. 2021; Man et al. 2019; Wójcik et al. 2021), cookies (Tanyitiku et al. 2024), salty biscuits (Arfa and Hassan 2023), extruded corn products (Igual et al. 2022), sponge cake (Ataei Nukabadi et al. 2021), rice waffles (Tanyitiku and Njombissie Petcheu 2025), pasta (Marchetti et al. 2018; Krawęcka et al. 2021) and noodles (Alemayehu et al. 2016)
Dairy products	Enhanced nutritional value and antioxidant capacity; improved probiotic viability; potential prebiotic effects; improved product stability during storage	Yogurt (Gülhan and Yangilar 2024), probiotic yoghurt (Kanani et al. 2018), yogurt bites (Kulaitienė et al. 2021), cheese (Sharma and Roy 2024)
Beverages and herbal infusion	Enrichment with phenolic antioxidants and micronutrients; improved antioxidant activity; potential anti-inflammatory and detoxifying effects; development of functional beverages	Tea (Said et al. 2015), juices (Bernaś and Fiutak 2023; Sharma and Roy 2024), soft drinks (Rad et al. 2016), guava fruits (Kalia et al. 2021)
Meat and fish products	Natural antioxidant and antimicrobial properties; reduced lipid oxidation; improved oxidative stability; enhanced nutritional profile and shelf life	Frankfurter type sausage (Alirezalu et al. 2016), Turkish dry-fermented sausage (Karabacak and Bozkurt 2008), rainbow trout (Alirezalu, Yaghoubi, et al. 2021), beef (Alirezalu, Movlan, et al. 2021)
Nutraceuticals and functional supplements	High levels of bioactive compounds with antioxidant, anti-inflammatory, anti-diabetic, and cholesterol-lowering properties; supports metabolic and immune health	Capsules, powders, herbal extracts, functional teas, dietary supplements (Kregiel et al. 2018; Mohammadian et al. 2024; Otles and Yalcin 2012; Sahal et al. 2025)

managing conditions such as diabetes, obesity, or metabolic syndrome. These functional properties align well with the growing consumer demand for low-GI, high-fiber, and nutrient-dense bakery foods.

Beyond nutritional improvements, nettle powder can also affect the technological and sensory properties of bakery products. Its high chlorophyll content imparts a natural green coloration to breads and pastries, which may enhance visual appeal and signal the presence of plant-based functional ingredients. Maietti et al. (2021) reported that nettle-enriched white bread exhibited elevated lutein (67.8 µg/g) and β-carotene (5.7 µg/g), confirming its potential as a natural colorant. However, excessive addition levels may introduce a slightly herbaceous or grassy flavor and may alter dough rheology due to the high fiber content (Tanyitiku and Njombissie Petcheu 2025). Đurović et al. (2020) reported increase bread hardness, decrease in bread elasticity, brightness (L^*), greenness (a^*), and yellowness (b^*) at 2.5% and 5% of NLP incorporation, bread characteristic, especially with 5.0% included soil taste, grass, soil, and herbs odor. Nettle addition in bread enhances water absorption, crumb greenish coloration, and antioxidant activity (Diddana et al. 2021; Đurović et al. 2020). Wójcik et al. (2021) observed a decrease in baking loss and bread volume, increase in porosity index of crumb when nettle extracts of 10–40 mg/mL were added to wheat bread. Lightness (L^*), greenness (a^*), and yellowness (b^*) decreased from 59.9 to 23.6, 2.1 to −3.4, and 20.4 to 14.2, respectively (Wójcik et al. 2021). Adding 0–2.5 g of NLP in 100 g of sponge cake, Ataei Nukabadi et al. (2021) reported that

2.5% nettle had the lowest hardness and the highest volume, moisture, springiness and cohesiveness, and organoleptic properties, including color, taste, flavor, and overall acceptability. Tanyitiku and Njombissie Petcheu (2025) reported a decrease in peak and trough velocity in waffle mixes (about 876 times and 1022 times, respectively) with an increase in sensory bitterness. Therefore, optimization of formulation and processing conditions is necessary to balance nutritional benefits with desirable sensory attributes.

In shelf-life extension, Arfa and Hassan 2023 reported total bacterial count was not detected until 1 month later at 3.08 to 2.30 log CFU/g in nettle incorporated salty biscuits. This increased gradually from 3.34 to 2.77 log CFU/g, respectively, and then 5.50, 4.91, and 4.56 log CFU/g at 6 months of storage. No fungi were detected. Additionally, reported water activity (a_w) values for nettle flour and nettle-incorporated corn cookies range between 0.24 and 0.59, levels that was found unfavorable for most spoilage microorganisms (Sahal et al. 2025; Tanyitiku et al. 2024).

5.2 | Dairy Products

Dairy products such as yoghurt, fermented milk, and cheese are widely recognized as effective carriers for bioactive compounds due to their rich nutrient matrix and widespread consumer acceptance. The incorporation of nettle into dairy matrices has attracted increasing attention in recent years because of its high content of phenolic compounds, flavonoids, vitamins, minerals,

and polysaccharides, all of which enhances the nutritional and functional quality of dairy products (Sharma and Roy 2024). Kanani et al. (2018) demonstrated that the incorporation of nettle extract into yoghurt exerted inhibitory effects on the growth of *Helicobacter pylori* while simultaneously enhancing the viability of *Bifidobacterium* species, suggesting its potential as an effective prebiotic ingredient. These improvements are largely attributed to the presence of bioactive compounds such as phenolic acids, flavonoids, minerals, and chlorophyll derivatives naturally present in nettle leaves. In yoghurt bite production, nettle extracts at 1% have been explored as natural fortifying agents capable of improving its phytochemical and nutritional value, including increasing K, P, Mg, Fe, Zn, and total phenolic contents (Kulaitienė et al. 2021).

Beyond antioxidant enhancement, nettle incorporation may also extend the shelf-life of dairy products. Research indicates that yoghurt fortified with nettle extracts can decrease the pH and increase its acidity up to 21 days during refrigerated storage with significant antibacterial effects on *Spinacia pneumoniae*, *K. pneumoniae*, and *P. aeruginosa* (Gülhan and Yangilar 2024). This improvement in microbial stability is believed to result from the presence of nettle-derived polysaccharides and other fermentable components that may act as prebiotic substrates, thereby promoting the growth and metabolic activity of probiotic cultures. Such interactions create a symbiotic effect in which plant bioactives and probiotic bacteria work together to enhance the functional value of the final product.

Nettle incorporation may also influence the physicochemical and sensory characteristics of yoghurt. While moderate levels of nettle extract or powder can enhance the nutritional profile without significantly altering product quality, higher concentrations may affect texture, flavor, and appearance. For instance, increased levels of nettle extract have been associated with slightly higher whey separation (syneresis) and a mild herbal flavor that may reduce consumer acceptability. The green pigmentation from chlorophyll can also modify the color of yoghurt, which may be perceived positively or negatively depending on consumer expectations. To overcome these challenges, researchers have suggested the use of optimized fortification levels or advanced delivery techniques such as microencapsulation of nettle extracts (Mohammadian et al. 2024). Microencapsulation can protect sensitive bioactive compounds, improve stability during processing and storage, and minimize undesirable impacts on flavor and texture. Additionally, encapsulation may enable controlled release of antioxidants and other functional components within the gastrointestinal tract, further enhancing their potential health benefits.

5.3 | Beverages and Herbal Infusions

One of the most common beverage applications of nettle is herbal tea prepared from dried leaves (Bhusal et al. 2022; Said et al. 2015). Studies investigating the antioxidant properties of nettle extracts demonstrated that water-based extracts (similar to herbal tea infusions) contained high levels of phenolic compounds and showed strong radical-scavenging activity in DPPH and ABTS assays (Flórez et al. 2022; Rad et al. 2016). The authors concluded that nettle aqueous extracts can serve as natural

antioxidant sources suitable for functional beverages. Another study explores the different methods of preparing nettle tea, its advantages, and its future potential in the health and wellness industry, thereby highlighting its nutritional value and medicinal benefits (Baruah and Rana 2025). The mineral-rich composition of nettle, particularly its high iron, calcium, and magnesium content, contributes to its reputation as a restorative herbal drink (Baruah and Rana 2025). Beyond traditional teas, nettle extracts are increasingly being incorporated into modern beverage formulations, including functional drinks, smoothies, fermented beverages, and plant-based juices (Said et al. 2015; Sharma and Roy 2024; Rad et al. 2016). The inclusion of nettle in such products can enhance nutritional value while providing a distinctive herbal flavor and natural green coloration derived from chlorophyll.

Nettle-based beverages are particularly attractive because the leaves contain a diverse array of bioactive constituents, including phenolic acids, flavonoids, carotenoids, chlorophylls, vitamins, and minerals (Rad et al. 2016). When nettle leaves are infused in hot water, many of these compounds are extracted into the beverage, resulting in drinks with significant antioxidant capacity (Said et al. 2015). According to dietary recommendations, the daily consumption of dried nettle leaves for medicinal purposes ranges from 1.2 to 18.0 g, and 15–45 mL of nettle juice (Bernaś and Fiutak 2023; Said et al. 2015). Some clinical and biomedical studies also support the potential health benefits of nettle beverages. For instance, research investigating nettle extracts demonstrated improvements in antioxidant enzyme activity and oxidative stress markers in 50 patients with type 2 diabetes, highlighting the potential of nettle-based drinks or extracts as functional dietary components (N. Namazi et al. 2012). In addition to their antioxidant properties, nettle beverages are often associated with various physiological benefits. Traditional medicine systems have long used nettle infusions to support detoxification, improve digestion, reduce inflammation, and alleviate symptoms of conditions such as anemia, arthritis, and urinary tract disorders (Bhusal et al. 2022). In addition, modern scientific studies have provided some support for these traditional uses by demonstrating antimicrobial, anti-inflammatory, and mild diuretic activities (Table 6).

Furthermore, nettle could serve as a natural preservative. Comparative analyses showed that nettle extracts display antimicrobial efficacy comparable or superior to other herbal preservatives such as oregano and rosemary (Elez Garofulić et al. 2021), making them valuable tools for controlling foodborne pathogens and spoilage microorganisms. However, formulation challenges remain, as high concentrations of nettle extract may impart a strong vegetal taste that may not be acceptable to all consumers. Therefore, nettle can be combined with other plant ingredients, such as mint, lemon, ginger, or fruit juices, to improve flavor balance and consumer acceptance.

5.4 | Meat and Fish Products

The incorporation of plant-derived ingredients into meat and fish products has gained increasing attention as the food industry seeks natural alternatives to synthetic preservatives. One of the primary challenges in meat and fish processing is lipid

oxidation, which leads to the development of rancid flavors, color deterioration, and reduced nutritional quality during storage. Nettle extracts have been shown to effectively inhibit oxidative processes due to their high concentration of phenolic antioxidants such as flavonoids and phenolic acids (Alirezalu, Movlan, et al. 2021). When incorporated into meat formulations, nettle extracts can reduce the formation of lipid oxidation products and improve the oxidative stability of processed meats (Karabacak and Bozkurt 2008). For instance, Alirezalu, Movlan, et al. (2021) demonstrated that 1% ϵ -PL and 9% nettle extract significantly lowered TBARS and TVB-N values as well as showed inhibitory effects against molds and yeast, total viable counts, and coliforms. By day 12, TVB-N values increased to 15.37 and 35.17 mg/100 g from 5.38 to 7.24 mg/100 g. pH values increased from 5.78 to 6.61. In rainbow trout, by day 12, treated samples with 3% nettle extract + 0.2% ϵ -PL and control samples had the lowest (8.74 log CFU/g) and highest (9.05 log CFU/g) amount of TVC, respectively (Alirezalu, Yaghoubi, et al. 2021). In Frankfurter-type sausages, nettle was found to reduce lipid oxidation by approximately 20% compared to the control, while total viable counts were 2 log₁₀ CFU/g lower after 45 days of refrigerated storage (Alirezalu et al. 2016). In fish fillets, it significantly reduced thiobarbituric acid reactive substances (TBARS) and total volatile basic nitrogen (TVB-N) values compared to untreated samples after 12 days at 4°C (Alirezalu, Yaghoubi, et al. 2021). These characteristics make nettle particularly suitable for improving the shelf life, nutritional value, and functional quality of meat and fish products and are attributed to the presence of potent antioxidant phenolics and flavonoids, including rutin, ferulic acid, naringin, kaempferol, myricetin, quercetin, ellagic acid, *p*-coumaric acid, and isorhamnetin (Alirezalu, Yaghoubi, et al. 2021; Arfa and Hassan 2023; Kalia et al. 2021).

In addition to their antioxidant effects, nettle-derived compounds may also exhibit antimicrobial activity against certain spoilage and pathogenic microorganisms (Kagula et al. 2026). This antimicrobial potential is attributed to various bioactive constituents, including phenolic compounds, organic acids, and secondary metabolites that can disrupt microbial cell membranes and metabolic pathways. As a result, nettle extracts have been investigated as natural preservatives in meat and fish products, potentially reducing the reliance on synthetic additives while supporting the development of cleaner-label food products.

Beyond preservation benefits, the addition of nettle powder or extracts can enhance the nutritional profile of meat-based foods. Nettle leaves contain significant amounts of dietary fiber, minerals such as iron and calcium, and various micronutrients that are often lacking in conventional meat products. Incorporating nettle into meat formulations may therefore contribute to the development of value-added products with improved functional and nutritional attributes. However, as with other plant-based ingredients, the level of nettle incorporation must be carefully optimized to maintain desirable sensory characteristics. High concentrations may impart a noticeable herbal flavor or alter the color of the final product due to the presence of chlorophyll pigments. Consequently, controlled formulation strategies are necessary to balance the functional advantages of nettle with consumer acceptability.

5.5 | Nutraceuticals and Functional Supplements

In addition to its direct incorporation into food, nettles have gained considerable attention in the nutraceutical and functional supplement industries. Nettle fits well within this category because its leaves contain a diverse range of phytochemicals with demonstrated health-promoting properties (Table 6). Nettle-based nutraceutical products are commonly available in various forms such as capsules, tablets, powdered extracts, herbal teas, tinctures, and concentrated liquid extracts (Toplicean et al. 2024). These preparations are typically standardized to ensure consistent levels of bioactive compounds. The popularity of nettle supplements is largely attributed to their reported therapeutic effects in managing several chronic conditions. For instance, nettle extracts have been widely studied for their potential role in alleviating symptoms associated with benign prostatic hyperplasia (BPH), whereas compounds such as lignans and phytosterols may influence hormone metabolism and reduce prostate inflammation (Nassiri-Asl et al. 2009; Qayyum et al. 2016). In a similar study, F. Namazi et al. (2018) reported a protective effect of *Urtica dioica* leaf hydro alcoholic extract against the establishment of atherosclerotic lesions in rat aorta, which was associated with positive effects on serum lipid profile without significant effect on antioxidant status.

Furthermore, nettle has been investigated for its potential benefits in metabolic health. Bioactive compounds present in nettle have demonstrated anti-diabetic properties by improving insulin sensitivity, reducing blood glucose levels, and modulating carbohydrate metabolism (Dar et al. 2013; N. Namazi et al. 2012; Rahmati et al. 2021). These effects are largely linked to the plant's rich phenolic and flavonoid content, which possess strong antioxidant and anti-inflammatory activities (N. Namazi et al. 2012). By reducing oxidative stress and chronic inflammation, nettle-based nutraceuticals may contribute to the prevention or management of metabolic disorders such as type 2 diabetes, cardiovascular diseases, and obesity (Rahmati et al. 2021). Another important aspect of nettle supplementation is its high mineral content, particularly iron, calcium, magnesium, and potassium (Tanyitiku and Njombissie Petcheu 2023). These micronutrients make nettle supplements attractive as natural dietary boosters that may help address nutritional deficiencies, especially in populations with limited access to diverse diets. Additionally, the presence of chlorophyll, carotenoids, and vitamin C further enhances the antioxidant potential of nettle-based products. Despite these promising health benefits associated with nettle nutraceuticals, further clinical studies are needed to establish standardized dosages, long-term safety, and mechanisms of action of nettle as a valuable ingredient in the expanding global nutraceutical market.

6 | Conclusion and Future Directions

The aim of this review was to synthesize current knowledge on the bioactive composition, processing approaches, and functional food applications of nettle, while evaluating its potential health-promoting properties. Nettle represents a sustainable, nutritionally rich functional food ingredient with considerable potential. Its incorporation into food formulations has been shown to enhance nutritional value, antioxidant capacity, and techno-functional performance. Despite these advantages,

several gaps remain in research and food applications of nettle leaves. First, substantial variability in composition—influenced by factors such as harvest stage, geographic origin, leaf maturity, and processing conditions—highlights the need for standardized protocols to ensure reproducibility and consistent quality. Second, the retention and stability of bioactive compounds during thermal and mechanical processing, as well as the balance between functional enhancement and sensory acceptability (e.g., color, flavor, and bitterness), require systematic optimization. Third, although numerous *in vitro* and *in vivo* studies support nettle's biological activities (including antioxidant, anti-inflammatory, and antidiabetic effects), well-designed human clinical trials remain limited, restricting the substantiation of health claims. Fourth, aspects related to agricultural production systems, regulatory evaluation, safety assessment, and consumer perception remain underexplored and should be addressed to support large-scale commercialization. Looking ahead, nettle lies at the intersection of nutrition, sustainability, and functional food innovation. Its integration into human diets offers significant potential to contribute to the development of health-oriented and sustainable food systems.

Author Contributions

Mary Nkongho Tanyitiku: conceptualization, data curation, formal analysis, writing – original draft, writing – review and editing. **Rakshya Pandit:** conceptualization, data curation, writing – review and editing. **Mihiri Vanniarachchy:** conceptualization, validation, writing – review and editing.

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The authors declare no conflicts of interest.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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