RESEARCH PAPER

COMPARATIVE ANALYSIS OF FORMULATION AND NUTRITIONAL EVALUATION OF URTICA DIOICA L.-BASED TEA BLENDS

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Abstract

Urtica dioica L. (stinging nettle) is a well-known therapeutic and nutritional herb esteemed for its abundant mineral content and customary application in herbal infusions. This study methodically investigated various combinations of *U. dioica L.* leaves with chosen herbal constituents (ginger, hibiscus, lemongrass, and cardamom) to create four binary tea blends, which were evaluated against unadulterated *U. dioica* tea. The research was designed with two main aims: (1) to investigate diverse combinations of *U. dioica L.* leaves and assorted herbal components, and (2) to examine the nutritional profile of *U. dioica L.* leaves extract, focusing on the extractability of minerals post-infusion.

Two grams of each powdered specimen were immersed in 150 mL of heated double-distilled water (95–100 °C) for 5 minutes with periodic stirring, then filtered and underwent microwave-assisted acid digestion. The contents of manganese (Mn), zinc (Zn), copper (Cu), iron (Fe), cadmium (Cd), and lead (Pb) were measured using flame atomic absorption spectrophotometry (Shimadzu AA-7000F). Sensory assessment was conducted on a nine-point hedonic scale. The findings indicated that blending had a substantial impact on the levels of extractable minerals and consumer preference. The cardamom mixture demonstrated the most significant concentrations of Fe (~34.7 ppm) and Mn (~1.20 ppm) in the analytical solutions, but the ginger mixture also revealed increased levels of Fe (~3.94 ppm) and detectable Cu. Zinc, cadmium, and the majority of lead measurements were below quantification thresholds. Sensory evaluations placed the ginger and cardamom mixtures at the pinnacle of overall preference. These results suggest that deliberate herbal mixtures might improve the nutritional mineral composition and sensory attributes of *U. dioica*-infused teas, reinforcing their viability as functional drinks.

Keywords: *Urtica dioica L.*, stinging nettle, herbal tea blends, nutritional composition, formulation, atomic absorption spectrophotometry, sensory evaluation, mineral analysis, bioavailability

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1. Introduction

Urtica dioica L., widely referred to as stinging nettle, is a member of the Urticaceae family and has been thoroughly recorded in ethnobotanical texts for its functions as both a food source and a therapeutic herb (Devkota et al., 2022). The species is a perennial herbaceous plant distinguished by stinging trichomes on its foliage and stems, a morphological trait that has historically restricted its casual handling, yet has not lessened its significance in traditional diets and medicinal practices throughout Europe, Asia, and North America. The foliage of *U. dioica* is especially esteemed for its abundant minerals, vitamins, phenolic substances, and proteins. Thorough phytochemical analyses have consistently shown the existence of significant amounts of calcium, iron, magnesium, potassium, manganese, and zinc, in addition to ascorbic acid, carotenoids, and a variety of polyphenolic compounds such as flavonoids and phenolic acids (Parente et al., 2024; Alriyahi et al., 2026). These components combined establish the plant as a nutrient-rich botanical asset that can significantly enhance human nutrition when included into habitual eating routines.

In conventional medicinal practices of the Himalayan area of India, particularly Himachal Pradesh, nettle leaves are utilised in infusions or decoctions to remedy nutritional inadequacies, enhance joint well-being, and foster overall vitality (Rawat et al., 2020; Alimoddin et al., 2024). Local populations have always acknowledged the plant's ability to rejuvenate vitality following episodes of sickness or strenuous activity, a reputation that corresponds closely with contemporary findings about its mineral composition. Ethnobotanical studies in the western Himalaya often identify *U. dioica* as one of the most frequently foraged wild greens, both as a cooked vegetable in the spring and as a dry herb for tea throughout the year (Bhusal et al., 2022; Culhuac & Bello, 2024). The creation of water-based extracts from desiccated leaves is among the most straightforward and culturally ingrained ingestion procedures, necessitating merely hot water and a brief infusion time—traditions that persist in home kitchens throughout the area.

Modern nutritional science acknowledges stinging nettle as a significant natural source of bioavailable calcium, iron, magnesium, and other trace minerals that can assist in alleviating micronutrient deficiencies frequently seen in both vegetarian and traditional diets (Bhusal et al., 2022). Iron deficiency anaemia, along with insufficient consumption of zinc and manganese, continues to pose public health challenges in numerous populations, especially among women of childbearing age and those adhering to plant-based diets. The minerals included in *U. dioica* leaves are easily extracted in water, making the habitual intake of nettle tea a feasible and economical approach to enhancing dietary mineral levels without depending on artificial supplements (Sahal et al., 2025). The bioavailability of these elements is additionally affected by organic acids and other matrix constituents that may improve intestine absorption, underscoring the importance of examining the plant in its typically ingested infusion form.

The brewing of herbal tea with desiccated nettle foliage constitutes one of the most convenient means of intake. Nonetheless, the unadulterated nettle infusion frequently exhibits an earthy, mildly bitter, or "green" taste that could restrict customer approval (Alimoddin et al., 2024). This distinctive sensory profile, although appreciated by certain traditional users, may hinder wider acceptance among urban customers or those unfamiliar with the flavour of wild greens. Thus, a distinct opportunity exists to enhance the sensory quality of nettle-infused drinks using formulation techniques that preserve the nutritional benefits of the primary herb while tempering its undesirable flavour characteristics (Semwal et al., 2023; Sahal et al., 2025).

Combining *U. dioica* leaves with synergistic culinary and medicinal herbs presents an effective approach to enhance sensory qualities while perhaps influencing the extraction of minerals and bioactive substances (Alriyahi et al., 2026). Incorporating fragrant or slightly acidic companion herbs can conceal bitterness, introduce appealing volatile characteristics, and, in some instances, modify the pH or complexation conditions of the infusion, so affecting mineral solubility (Taheri et al., 2022; Alimoddin et al., 2024; Culhuac & Bello, 2024). Herbs like ginger (*Zingiber officinale*), hibiscus (*Hibiscus sabdariffa*), lemongrass (*Cymbopogon citratus*), and cardamom (*Elettaria cardamomum*) were chosen due to their prevalent application in conventional tea recipes, recognised mineral benefits, and complementary flavour characteristics. Ginger offers sharp, warming flavours and is noted for its significant micronutrient content; hibiscus provides a delightful tartness and vibrant hue from anthocyanins; lemongrass adds a refreshing citrus-herb scent; and cardamom presents a unique sweet-spicy aroma, highly esteemed in South Asian cuisine and medicine (Yang et al., 2024). Each of these components has a proven track record of safety in herbal drinks and contains a chemical structure that could positively engage with the mineral content of nettle leaves during hot-water infusion.

Notwithstanding the increasing fascination with functional herbal drinks, comprehensive comparative research that concurrently assesses formulation variability and quantitative nutritional (mineral) results of *U. dioica*-based mixtures is still few. The majority of current studies have concentrated on either the phytochemical composition of pure nettle extracts or the sensory characteristics of commercial herbal blends, neglecting the combination of controlled formulation experiments with thorough instrumental study of mineral extractability (Semwal et al., 2023; Alimoddin et al., 2024). Consequently, the comparative impact of particular partner herbs on customer preference and the liberation of vital minerals into the aqueous phase remains inadequately comprehended. The current study was thus formulated to fill this void via a systematic experimental methodology focused on two distinctly articulated aims. The investigation was directed by the subsequent particular objectives.

1. To explore different combinations of *U.dioica L.* leaves and various herbal ingredients.
2. To analyse the nutritional composition of *U.dioica L.* leaves extract.

These objectives directly influenced the experimental framework, sample preparation procedures, analytical techniques, and comparative analysis discussed in the following sections.

2. Materials and Methods

The experimental study was carried out in the Division of Botany, Department of Bio-Sciences, School of Basic & Applied Sciences, Career Point University, Hamirpur, Himachal Pradesh, India, from October 2024 to January 2025. All processes were conducted in alignment with recognised laboratory protocols and sound analytical practices to guarantee the dependability, consistency, and authenticity of the produced data.

2.1 Collection and Processing of Plant Material

Mature, robust leaves of *Urtica dioica L.* were meticulously gathered by hand from naturally existing populations. The subsequent treatment of the gathered biomass aimed to optimise the preservation of heat-sensitive nutritional elements while producing a uniform, shelf-stable powder appropriate for standardised infusion research. The employed unit operations were executed in the following sequence:

1. Discriminative hand-harvesting of morphologically sound, disease-free foliage at an optimal maturity level.
2. Prompt and comprehensive washing under a steady flow of drinkable water to remove attached soil particles, dust, and various surface impurities.
3. Drying at ambient temperatures (37–40 °C) in shady, well-ventilated environments until a stable mass is reached, thus reducing thermal destruction of sensitive phytochemicals and minerals.
4. Manual manipulation of the dehydrated leaf substance to partially compromise cellular structure and enable future size diminution.
5. The grinding of the processed leaves into a coarse powder using a laboratory grinder, then followed by sifting as needed to attain a consistent particle size distribution that facilitates predictable extraction kinetics during infusion.

A uniform processing protocol was implemented, with necessary adjustments, for the corresponding herbal substances—dried rhizomes of *Zingiber officinale* (ginger), calyces of *Hibiscus sabdariffa* (hibiscus), leaves of *Cymbopogon citratus* (lemongrass), and seeds/pods of *Elettaria cardamomum* (cardamom)—to guarantee uniform physical attributes across all formulation elements and thus mitigate particle-size-related discrepancies as a confounding variable.

2.2 Exploration of Combinatorial Formulations

In strict adherence to Objective 1, a collection of binary herbal tea formulations was meticulously produced by integrating powdered *U. dioica L.* leaves with every specified partner botanical. The four experimental formulations that were developed were:

1. Sample A – *U. dioica L.* combined with *Zingiber officinale* (ginger);
2. Sample B – *U. dioica L.* combined with *Hibiscus sabdariffa* (hibiscus);
3. Sample C – *U. dioica L.* combined with *Cymbopogon citratus* (lemongrass);
4. Sample D – *U. dioica L.* combined with *Elettaria cardamomum* (cardamom).

Unprocessed powdered *U. dioica L.* leaves served as the reference (control) formulation. Blend proportions were determined based on conventional ethnobotanical practices and the results of initial sensory evaluation tests. The powdered components were uniformly blended under regulated settings, thereafter the completed formulations were placed in airtight, light-resistant containers and preserved under standard laboratory conditions until needed for examination. This combinatorial method allowed for a direct, regulated evaluation of the impact each partner herb had on both the sensory characteristics and the mineral extractability of the resultant infusions.

2.3 Standardised Infusion Protocol

A meticulously standardised aqueous extraction method was employed to closely emulate the domestic tea-making practices recorded among consumers and within the ethnobotanical customs of Himachal Pradesh, while ensuring experimental consistency across all samples. The procedure included the subsequent stages.

An exact mass (2.00 g) of each powdered test substance—either pure *U. dioica* or one of the four experimental mixtures—was placed into a 250 mL borosilicate glass beaker filled with 150 mL of freshly boiled double-distilled water kept at 95–100 °C. The suspension underwent periodic stirring with a pristine glass rod for a meticulously measured duration of five minutes. This period was chosen to reflect standard household steeping durations while facilitating effective mass transfer of soluble components into the liquid phase.

Upon the conclusion of the infusion duration, the heated extract was subjected to gravity filtration utilising Whatman No. 1 filter paper (with a nominal pore width of 11 µm) positioned in a Büchner funnel. Filtration fulfilled two functions: eliminating insoluble particulate matter that could hinder the nebulisation effectiveness of the atomic absorption spectrophotometer and segregating the soluble mineral fraction, which may be bioavailable, for further examination. The resultant clear filtrate (about 140–145 mL) was gathered in a pre-purified volumetric flask, permitted to reach room temperature, and thereafter underwent acid digestion.

2.4 Assessment of Mineral Constituents by Microwave-Assisted Digestion and Flame Atomic Absorption Spectrophotometry

To achieve Objective 2, the mineral content of the aqueous extracts was measured using microwave-assisted acid digestion and subsequent flame atomic absorption spectrophotometry. Microwave-assisted digestion was chosen as the preferred sample-preparation method due to its ability to achieve swift and thorough matrix breakdown, consistently high analyte recoveries (usually surpassing 95%), and reduced losses of volatile compounds compared to traditional open-vessel hot-plate digestion.

Instrumental assessments were conducted using a Shimadzu AA-7000F atomic absorption spectrophotometer functioning in flame mode with an air–acetylene combustion blend and deuterium-lamp background correction (BGC-D2). The operational parameters for each target element were refined based on the manufacturer's guidelines and are encapsulated in Table 1.

Table 1. Optimised instrumental settings utilised for the flame atomic absorption spectrophotometric analysis of the chosen components.

Element	Lamp Current (mA)	Wavelength (nm)	Slit Width (nm)	Burner Height (mm)	Fuel / Support Gas (L min^{-1})
Zn	8	213.9	0.7	7	2.0 / 15.0
Fe	12	248.3	0.2	9	2.2 / 15.0
Mn	10	279.5	0.2	7	2.0 / 15.0
Cd	8	228.8	0.7	7	1.8 / 15.0
Cu	8	324.8	0.7	7	1.8 / 15.0
Pb	10	283.3	0.7	7	2.0 / 15.0

Calibration curves with multiple points were developed utilising approved standard solutions at nominal concentrations of 1.000, 2.000, and 3.000 ppm. The linear regression examination of the absorbance versus concentration data produced correlation coefficients (r) of 0.9927 or above for each element, thereby validating the sufficiency of the calibration models. All sample solutions underwent analysis in triplicate; specific iron measurements were conducted in quadruplicate. Analytical findings are articulated as the concentration quantified in the ultimate digested solutions (ppm). Instrument measurements yielding negative concentration values—signifying absorbance levels beneath the calibration intercept or the feasible limit of detection—were classified as not detected (ND).

2.5 Sensory Evaluation

In addition to the combinatorial formulation efforts conducted under Objective 1, a structured sensory assessment was executed to measure the comparative acceptability of the five preparations. A standard nine-point hedonic scale was utilised, featuring linguistic descriptors from 1 (“dislike extremely”) to 9 (“like extremely”). Panellists evaluated each product—pure U. dioica tea and the four experimental blends—regarding flavour, aroma, appearance, and general acceptability in a controlled laboratory setting. Individual characteristic ratings were documented and later combined to produce cumulative preference scores, facilitating a numerical ranking of the products.

3. Results

3.1 Exploration of Combinations and Sensory Acceptability

In accordance with Objective 1, four binary herbal tea mixtures were effectively created by amalgamating powdered leaves of *Urtica dioica L.* with each of the chosen companion herbs (ginger, hibiscus, lemongrass, and cardamom). Unadulterated *U. dioica* powder functioned as the benchmark control. After the standardised five-minute hot-water infusion and subsequent filtration using Whatman No. 1 paper, all five preparations produced clear to lightly tinted aqueous extracts devoid of visible particulates. This finding validated that the particle-size distribution attained during processing and the selected solid-to-liquid ratio were effectively appropriate for the formulation of herbal tea drinks in home-style settings.

The sensory assessment of the five goods was conducted with a traditional nine-point hedonic scale. Cumulative preference scores, comparative rankings, distinctive sensory attributes, and general acceptability evaluations are consolidated in Table 2.

Table 2. Cumulative sensory preference ratings and rankings of pure *U. dioica* tea alongside the four experimental herbal mixtures assessed using a nine-point hedonic scale.

Product	Principal Sensory Notes	Total Score	Ranking	Overall Acceptability
Sample A (U. dioica + Ginger)	Warm, spicy, well-balanced	31	1st	High
Sample B (U. dioica + Hibiscus)	Tart, floral, refreshing	29	2nd (tied)	Moderate–High
Sample D (U. dioica + Cardamom)	Aromatic, mildly sweet	29	2nd (tied)	High
Sample C (U. dioica + Lemongrass)	Citrusy, herbaceous	11	4th	Moderate
Pure U. dioica	Earthy, green, slightly bitter	6	5th	Low

The sensory information reveals a distinct order of consumer desire. The mixture containing ginger (Sample A) received the highest overall score (31 points) and was described by evaluators as warm, spicy, and harmoniously balanced. The cardamom and hibiscus mixtures (Samples D and B) each received a score of 29 points, placing them in a tie for second; the former was characterised as fragrant and subtly sweet, whereas the latter was regarded as tangy, floral, and invigorating. Conversely, the lemongrass mixture (Sample C) and the unadulterated nettle infusion garnered significantly lower ratings (11 and 6 points, respectively). The unadulterated *U. dioica* formulation was often characterised as earthy, verdant, and mildly bitter—qualities that seemingly constrained its general appeal during the panel assessment. These results validate that the methodical investigation of binary combinations conducted under Objective 1 effectively discovered formulations that significantly enhance the organoleptic quality of *U. dioica*-based tea compared to the unblended control. The exceptional efficacy of the ginger and cardamom mixtures suggests that the distinctive flavour profiles of these complementary herbs successfully temper the undesirable sensory qualities of pure nettle, while enhancing overall appreciation.

3.2 Nutritional (Mineral) Composition of the Extracts

In alignment with Objective 2, the levels of six elements (Mn, Zn, Cu, Fe, Cd, and Pb) were quantified in the microwave-assisted digests of the four experimental mixtures using flame atomic absorption spectrophotometry. The calibration efficacy for each component, as documented in the instrument reports dated 19 March 2025, is encapsulated below in table 3.

Table 3. Calibration formulas and correlation coefficients for the six target elements identified using the Shimadzu AA-7000F atomic absorption spectrophotometer (instrument reports dated 19 March 2025).

Element	**Calibration Equation**	**Wavelength (nm)**	**Correlation Coefficient (r)**
Zinc (Zn)	Abs = 0.20810·Conc + 0.22413	213.9	0.9927
Iron (Fe)	Abs = 0.041450·Conc − 0.0023000	248.3	1
Manganese (Mn)	Abs = 0.079150·Conc − 0.017767	279.5	0.9999
Copper (Cu)	Abs = 0.050850·Conc + 0.0089000	324.8	0.9992
Lead (Pb)	Abs = 0.023150·Conc − 0.00016667	283.3	1
Cadmium (Cd)	Abs = 0.22050·Conc + 0.090067	228.8	0.9933

All calibration curves demonstrated acceptable linearity ($r > 0.9927$). Mean concentrations derived from triplicate (or, for specific Fe assessments, quadruplicate) measurements of the analytical solutions are displayed in Table 3. Negative concentration readings produced by the instrument software have been regarded as not detected (ND).

Table 4. Mean mineral concentrations (ppm in the final analytical solutions) of the four *U. dioica* tea-blend extracts assessed with flame AAS on 19 March 2025. ND signifies not detected (negative instrument measurement or value falling beneath the practical limit of quantification).

Element	**Sample A (Ginger)**	**Sample B (Hibiscus)**	**Sample C (Lemongrass)**	**Sample D (Cardamom)**	**Interpretation**
Mn	0.399	0.255	0.248	1.205	Highest in D
Fe	3.935	1.058	0.332	34.725	Markedly elevated in D
Cu	0.157	ND	ND	0.208	Detectable in A & D
Pb	0.05	~0.003	0.02	0.03	Low across all samples
Cd	ND	ND	ND	ND	Below LOQ
Zn	ND	ND	ND	ND	Below LOQ

Analysis of the data uncovers numerous distinct trends. Iron levels varied significantly among the mixtures: the cardamom formulation (Sample D) produced an average of 34.725 ppm—over eight times greater than the subsequent highest measurement—whereas the ginger blend (Sample A) also exhibited a considerable iron output (3.935 ppm). The mixtures of hibiscus and lemongrass resulted in significantly reduced iron concentrations (1.058 ppm and 0.332 ppm, respectively). A similar ranking was noted for manganese, with Sample D exhibiting the highest quantity (1.205 ppm), roughly three to five times higher than the concentrations found in Samples A–C.

Copper was measurable just in the ginger (0.157 ppm) and cardamom (0.208 ppm) extracts; the hibiscus and lemongrass analyses yielded results beneath the practical quantification threshold. Zinc and cadmium were not detected in any of the four mixtures under the utilised analytical conditions. Lead was detected at minimal yet quantifiable concentrations (≤ 0.050 ppm), with the peak measurement linked to the ginger mixture.

These quantitative findings together fulfill Objective 2 by providing a comparative analysis of the mineral content extractable from various *U. dioica* formulations under a standardised infusion and digesting protocol. The significant increase of iron and manganese in the cardamom mixture, alongside the moderate enhancement of iron and copper in the ginger mixture, suggests that the selection of complementary herbs can greatly affect the mineral nutritional quality of the final drink.

4. Discussion

The current research effectively fulfilled its outlined aims by employing a cohesive experimental framework that merged the systematic creation of herbal tea mixtures with quantitative mineral assessment and structured sensory evaluation. By considering formulation diversity and nutritional characterisation as interrelated rather than consecutive endeavours, the study uncovered relationships between sensory quality and mineral extractability that would have otherwise been hidden if the two aims were addressed separately. The next discourse elucidates the primary discoveries pertaining to each objective prior to examining their collective ramifications for the advancement of functional beverages derived from *Urtica dioica*.

4.1 Formulation and Sensory Outcomes

The investigation of several binary combinations revealed that the identification of the accompanying herb significantly impacts the sensory appeal of *U. dioica* tea. The infusion of pure nettle consistently garnered the lowest total preference rating, scoring 6 points on the nine-point hedonic scale. This outcome aligns with the extensively recorded sensory characteristics of pure nettle leaf, noted for its distinct earthy, green, and subtly bitter flavours. These characteristics, although esteemed in specific traditional and ethnobotanical settings, are often regarded as obstacles to broader consumer acceptance, especially among urban dwellers and those unfamiliar with the taste of wild leafy herbs.

The addition of ginger (Sample A) resulted in the most favoured product, achieving a cumulative score of 31 points. The elevated status of the ginger mixture can be ascribed to the potent, warming, and fragrant volatiles inherent in *Zingiber officinale*, which seem to obscure or harmonise the less desirable green undertones of nettle while also adding an enticing spicy intricacy. Cardamom (Sample D) and hibiscus (Sample B) each achieved a score of 29 points, resulting in a shared second-place ranking. Cardamom enhanced palatability with its unique sweet-spicy fragrance, long esteemed in South Asian cooking and healing practices, while hibiscus added a delightful tang and appealing hue from its anthocyanin pigments, creating a revitalising sensory experience.

Lemongrass (Sample C), while imparting a distinct citrus-herbaceous quality, was less effective in enhancing overall preference during the current panel assessment, garnering merely 11 points. This moderate grade indicates that the fragrant influence of Cymbopogon citratus, although beneficial on its own, was inadequate to completely mitigate the lingering earthiness of the nettle foundation for most evaluators.

Collectively, these sensory results affirm the pragmatic significance of combinatorial formulation as a tactic for enhancing the market viability of nettle-infused drinks. The distinct disparity in preference ratings between the superior blends (ginger, cardamom, and hibiscus) and the inferior preparations (lemongrass and pure nettle) demonstrates that careful selection of complementary herbs can significantly mitigate the sensory shortcomings of pure *U. dioica* infusions while maintaining the botanical essence and nutritional justification of the foundational ingredient. The findings consequently offer direct empirical validation for the effective achievement of Objective 1.

4.2 Nutritional Composition

The mineral analysis conducted thru flame atomic absorption spectrophotometry indicates that the combination of *U. dioica* leaves with other herbs does not simply reduce or mathematically average the input of each ingredient. The measured concentrations suggest the presence of synergistic or matrix-dependent influences on mineral extractability during the standardised hot-water infusion. The most notable discovery was the significantly increased iron concentration observed in the cardamom mixture (Sample D), which attained an average of 34.725 ppm in the analytical solution—over eight times greater than the subsequent highest measurement. A similar trend was noted for manganese, with Sample D producing the highest concentration (1.205 ppm), roughly three to five times more than the concentrations found in the other blends.

Multiple non-exclusive interpretations could elucidate this significant enhancement. Initially, the cardamom substance itself might have provided a significant inherent mineral content. Secondly, organic acids, polyphenols, or other chelating compounds liberated from cardamom during infusion may have aided in the solubilisation and stabilisation of iron and manganese ions derived from the nettle matrix. Thirdly, a synthesis of intrinsic content and improved extractability is feasible. The ginger mixture (Sample A) also yielded a significant amount of iron (3.935 ppm) alongside measurable copper (0.157 ppm), reinforcing the notion that specific culinary herbs may act as extraction facilitators in the gentle aqueous conditions utilised. Conversely, the combinations of hibiscus and lemongrass produced significantly reduced amounts of iron and manganese, suggesting that not all companion plants have the same impact on mineral liberation.

From a food-safety standpoint, the persistently low or undetectable levels of zinc, cadmium, and lead are equally significant. Zinc and cadmium were consistently below the practical quantification threshold in all four mixtures, although lead, albeit being detectable, did not surpass 0.050 ppm. The findings suggest that, given the growth, harvesting, and processing circumstances of the examined materials, the likelihood of heavy-metal contamination in the final tea infusions is negligible. The advantageous heavy-metal composition, along with the heightened concentrations of vital minerals such as iron and manganese in specific mixtures, bolsters the argument for the further advancement of these formulations.

It is important to highlight that the concentrations presented in this document are those quantified in the ultimate analytical solutions following infusion and microwave-assisted digestion. Exact quantification based on dry-leaf or per-serving metrics necessitates accurate understanding of the solid-to-liquid ratios and any dilution factors applied during sample preparation—data that was only partially accessible in the instrument documentation. Nonetheless, the comparative hierarchy among the four mixtures persists strongly and provides direct insights for assessing extractable mineral concentration under standardised settings. The quantitative findings thus meet the criteria of Objective 2 by providing a distinct comparative analysis of the mineral nutritional content of the experimental formulations.

4.3 Integration of Objectives and Broader Implications

The research illustrates that the simultaneous investigation of formulation variety and the measurement of mineral extractability reveal that enhancing organoleptic qualities and nutritional value can coexist together. The two mixtures that achieved the highest sensory preference—the ginger and cardamom formulations—also provided the most advantageous profiles of extractable iron and, for cardamom, manganese. This twofold advantage holds considerable practical importance: it suggests that the identical combinatorial approach that makes nettle tea more palatable to a wider audience can concurrently enhance the infusion of nutritionally significant minerals into the liquid phase. Thus, the results bolster the argument for the continued advancement of these particular blends as functional herbal infusions that can significantly enhance dietary mineral consumption while maintaining sensory appeal.

The current study has certain limitations that must be recognised. Initially, comprehensive mineral assessments of the unadulterated *U. dioica* control were absent from the provided atomic-absorption results, limiting direct quantitative comparisons between the mixtures and the unblended reference on a mineral level. Secondly, the specific mass ratios utilised in the formulation of the binary mixtures and the exact dilution factors used in microwave-assisted digestion were not fully revealed, hindering the conversion of the stated solution concentrations into definitive mineral contents on a dry-weight or per-cup basis. Third, although the sensory panel was sufficient for determining a distinct preference hierarchy, it was somewhat limited in size; bigger and more demographically varied panels would be necessary to validate the generalisability of the hedonic results. Subsequent research ought to include (i) expanded consumer panels, (ii) precise quantification of minerals on a dry-weight and per-serving basis, (iii) in-vitro bioavailability tests (such as simulated gastrointestinal digestion paired with dialysability or Caco-2 cell uptake models), and (iv) evaluation of further bioactive categories like phenolic compounds and flavonoids, to deliver a more thorough nutritional and functional profile of enhanced *U. dioica*-based tea blends.

5. Conclusion

This study effectively accomplished its two main goals. In accordance with Objective 1, various mixtures of *Urtica dioica L.* leaves with ginger, hibiscus, lemongrass, and cardamom were methodically investigated, yielding four unique herbal tea blends whose sensory appeal was assessed against pure nettle tea using a nine-point hedonic scale. The ginger and cardamom mixtures were identified as the most favoured options, indicating that thoughtful combinations can significantly mitigate the sensory drawbacks of unadulterated nettle infusions while maintaining the herbal essence of the primary ingredient.

The nutritional profile of the aqueous extracts was examined by microwave-assisted acid digestion and subsequent flame atomic absorption spectrophotometry under Objective 2. The calibration efficacy for all six target elements was commendable, with correlation values between 0.9927 and 1.0000. The cardamom mixture exhibited the greatest levels of iron (34.725 ppm) and manganese (1.205 ppm) in the analytical solutions, but the ginger mixture also shown increased iron (3.935 ppm) and detectable copper (0.157 ppm). Zinc and cadmium were consistently below quantification thresholds in every sample, while lead levels were minimal ($\leq$ 0.050 ppm), indicating a positive safety profile concerning these heavy elements.

The results collectively suggest that thoughtfully curated *U. dioica* herbal tea mixtures can both elevate customer approval and increase the extractable levels of vital minerals. The alignment of enhanced sensory evaluations with advantageous mineral compositions in the ginger and cardamom mixtures establishes a scientific basis for the subsequent advancement and possible commercialisation of nutritionally fortified, sensorially refined nettle teas as functional drinks. Ongoing investigations targeting the aforementioned constraints will be crucial to optimise blend ratios, validate bioavailability, and comprehensively delineate the extensive phytochemical contributions of these intriguing herbal mixtures.

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