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Nutritional and bioactive compound profiling of 13 ornamental and edible flowers supports their potential as functional ingredients in sustainable food systems

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This study characterized the nutritional composition and bioactive compound profile of thirteen ornamental and edible flower species to support discussion on their potential as functional ingredients within sustainable food systems. Proximate composition (carbohydrates, proteins, lipids, ash, and moisture), total phenolic and flavonoid contents, and antioxidant capacity (ABTS, DPPH, and FRAP) were determined, with selected phenolic markers identified by HPLC-DAD. The results revealed pronounced compositional variability among species and identified rutin and caffeic acid as major bioactive markers, reflecting the functional relevance of these plant resources. Importantly, many of the species evaluated are ornamental plants commonly cultivated in home gardens, urban landscapes, or occurring spontaneously, yet rarely recognized for their edible potential. Overall, the findings provide a scientific evidence base to guide future research and innovation focused on the valorization of underutilized ornamental plants as nutrient-rich, plant-based ingredients, contributing to sustainability-oriented food systems.

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Sustainability spotlight

This study addresses the need to expand sustainable and biodiversity-based food and ingredient sources by investigating underexplored ornamental and edible flowers. Although often available in ecosystems and production systems, these floral species remain undervalued due to a lack of public awareness about their nutritional and chemical potential. By characterizing their phenolic and flavonoid compounds with antioxidant properties, the work advances scientific understanding of renewable floral resources and their functional value for food applications. The study promotes the sustainable use of natural biodiversity and the development of low-impact, circular bioeconomy products, aligning with the United Nations Sustainable Development Goals (SDGs) 2, 3, 9, 12, and 15.

1. Introduction

Food and nutritional security have been central pillars in global discussions on sustainability, especially considering population growth, increasing pressure on production systems, and climate change. In this context, expanding the global food base through the sustainable use of non-conventional plant species emerges as an essential strategy to reduce vulnerabilities, diversify diets, and enhance biodiversity conservation value.[1–3] The rational use of underutilized plant resources is also aligned with the United Nations Sustainable Development Goals (SDGs 2, 3, 9, 12 and 15), promoting the transition toward more resilient, local, and environmentally balanced food systems.[4,5]

Among promising alternatives, non-conventional edible plants, popularly known in Brazil as PANCs, have received increasing attention due to their nutritional and functional potential while representing an important biological reservoir of bioactive compounds.[6,7] Within this group, edible flowers stand out not only for their diversity of colors, shapes, and aromas but also for their bioactive compound profile and added value to the food and natural-products industries.[8–10] In this context, the term "edible" refers to flower species for which consumption has been reported in the scientific literature or traditional use, without implying universal safety or regulatory approval. Many of these flowers are traditionally cultivated for ornamental purposes but also exhibit sensory and nutritional characteristics compatible with human consumption.[11–13]

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The utilization of ornamental flowers with edible potential is closely linked to the principles of the circular bioeconomy, as it promotes the full use of plant biomass and the valorization of underexploited raw materials. This approach encourages short production chains, local income generation, and the reduction of plant-resource waste, in line with green-economy and sustainable-innovation goals.[14]

From a chemical and nutritional standpoint, flowers exhibit wide compositional variability influenced by genetic, environmental, and seasonal factors. The characterization of basic parameters such as moisture, proteins, lipids, carbohydrates, and fibers provides essential information to assess their technological feasibility and energetic value. Furthermore, the presence of bioactive compounds, particularly phenolics and flavonoids, has been associated with antioxidant-related properties that may contribute to food quality and stability. Systematic compositional analyses are therefore essential to support the rational incorporation of edible flowers into food formulations.[11,15,16]

Despite increasing scientific interest, research on ornamental and edible flowers remains concentrated on a limited number of well-studied species, such as *Calendula officinalis*, *Rosa* spp., *Dianthus chinensis*, *Tagetes erecta*, *Tropaeolum majus*, and *Centaurea cyanus*, predominantly of European and Asian origin.[17–20] This predominance results in a shortage of systematic data on tropical native and ornamental flowers, hindering methodological standardization, toxicological assessments, and the development of regulatory frameworks necessary for their safe and functional use in food and nutraceutical products.[21,22]

In this context, the present study aims to characterize the physicochemical and functional profile of thirteen ornamental and edible flower species belonging to distinct botanical families and ecological origins. By integrating nutritional and bioactive compound data under a sustainability-oriented approach, this work seeks to contribute to the scientific understanding of edible ornamental flowers and provide technical support for their safe and innovative application in food products.

2. Materials and methods

2.1 Plant material

Thirteen species of ornamental and edible flowers were evaluated: *Abutilon megapotamicum* St.-Hil. & Naudin, *Alpinia purpurata* Vieill., *Bougainvillea glabra* Choisy, *Petrea volubilis* L., *Pelargonium hortorum* L.H. Bailey, *Ixora coccinea* L., *Megaskepasma erythrochlamys* Lindau, *Murraya paniculata* (L.) Jack, *Talinum fruticosum* (L.) Juss., *Thunbergia erecta* (Benth.) T. Anderson, *Arachis pintoi* Krapov. & W.C. Greg., *Plumbago auriculata* Lam., and *Antigonon leptopus* Hook. & Arn.

The flowers were collected from public areas in Vila Velha, Espírito Santo, Brazil. All species were taxonomically identified and deposited in the VIES Herbarium of the Federal University of Espírito Santo (UFES), Vitória, Brazil.

2.2 Sample preparation and processing

A standardized extraction protocol was applied using 70% ethanol (NEON®) at a 1 : 10 (w/v) sample-to-solvent ratio. Fresh petals and bracts were immersed in the solvent and subjected to maceration under constant stirring at room temperature for 24 h to ensure adequate diffusion of bioactive compounds. The resulting extracts were filtered and concentrated by rotary evaporation under reduced pressure at 40 °C. Concentrated extracts were subsequently lyophilized and stored at 4 ± 2 °C until analysis to preserve compound stability.[23]

Petals and bracts, previously washed in running water, were used in the assays. In some species, both flowers and bracts were analyzed due to their morphological similarity and biological functions related to pigmentation and protection. For proximate composition analyses, fresh samples were used immediately after collection. For chromatographic and bioactive compound analyses, samples were frozen and subsequently.[23]

2.3 Proximate composition

Proximate composition was determined according to the official methods of the Association of Official Analytical Chemists (AOAC, 2019).[24] Moisture content was determined gravimetrically by oven drying at 105 °C until constant weight. Ash content was measured by incineration in a muffle furnace at 550 °C. Protein content was estimated by the Kjeldahl method using a nitrogen-to-protein conversion factor of 6.25. Lipid content was determined by Soxhlet extraction with petroleum ether. Carbohydrate content was calculated by difference, subtracting the total percentages of moisture, proteins, lipids, and ash from 100.

2.4 Chemical composition and general analytical conditions

The antioxidant activity of the extracts was evaluated using electron-transfer (ET) methods in 96-well microplates, with spectrophotometric readings performed on a SpectraMax® 190 microplate reader. Samples were prepared in 70% ethanol (NEON®) and analyzed in triplicate. Absorbance readings were taken at specific wavelengths for each assay, and the results were expressed either as percentage of inhibition (I%) or as half maximal inhibitory concentration (IC_{50}), calculated from the linear regression equation of the corresponding calibration curves.[25]

The percentage of inhibition (I%) was calculated according to the following equation:

$$I\% = [(Abs_0 - Abs_1)/Abs_0] \times 100$$

where Abs_0 represents the absorbance of the blank and Abs_1 that of the sample.

In addition to antioxidant assays, the total phenolic and flavonoid contents were determined under the same instrumental conditions described above, and the results were expressed as milligrams of standard equivalents per gram of sample (mg E per g).

2.5 Antioxidant activity assays

The wavelengths used for the DPPH (517 nm), $ABTS^+$ (734 nm), and FRAP (595 nm) assays correspond to the maximum absorbance of the DPPH radical, $ABTS^+$ radical cation, and ferrous-tripyridyltriazine complex, respectively, allowing accurate monitoring of radical scavenging or reducing reactions.

2.5.1 DPPH radical-scavenging assay. The DPPH assay was performed according to Brand-Williams[26] with adaptations. In a 96-well microplate, 30 μL of extract and 270 μL of DPPH solution (0.06 mM in 70% ethanol) were added. Samples were incubated for 60 minutes in the dark, and absorbance was read at 517 nm. The blank was prepared by replacing the extract with 70% ethanol.

2.5.2 $ABTS^+$ radical-cation decolorization assay. The $ABTS^+$ assay was performed as described by Re[27] with adaptations. The radical solution was obtained by reacting ABTS (7 mM) with potassium persulfate (2.45 mM) and incubating for 16 hours in the dark. After dilution to an absorbance of 1.0 ± 0.020 at 734 nm, 30 μL of extract and 270 μL of $ABTS^+$ solution was mixed. After 6 minutes of incubation, absorbance was measured at 734 nm. The blank was prepared by replacing the extract with 70% ethanol.

2.5.3 Ferric reducing antioxidant power (FRAP) assay. The FRAP assay was conducted according to Benzie and Strain[28] with modifications. A mixture containing 30 μL of extract and 270 μL of FRAP reagent was incubated for 10 minutes, and absorbance was measured at 595 nm. The blank consisted of 70% ethanol instead of extract.

2.6 Determination of total phenolic and flavonoid contents

2.6.1 Total phenolic content (TPC). The total phenolic content was determined by the Folin–Ciocalteu method based on a redox reaction between the reagent and phenolic compounds.[29] In a 96-well microplate, 25 μL of extract, 10 μL of 10% Folin–Ciocalteu reagent (Sigma®), and 215 μL of 7.5% sodium carbonate (Sigma®) were added. After 3 minutes, the absorbance was read at 715 nm. The blank was prepared with 70% ethanol. Calibration curves were constructed with gallic acid standards over the validated linear range. Samples above the curve limit were diluted and reanalyzed to ensure linearity. Results were expressed as mg GAE per g (gallic acid equivalents per gram of sample).

2.6.2 Total flavonoid content (TFC). The total flavonoid content was determined by the aluminum-chloride ($AlCl_3$) colorimetric method according to Xu and Chang[30] with modifications. The method is based on complex formation between aluminum ions and hydroxyl groups of flavonoids. In each well, 180 μL of extract and 15 μL of 2.5% sodium nitrite ($NaNO_2$, Sigma®) were added. After 6 minutes, 15 μL of 10% aluminum chloride ($AlCl_3$, Sigma®) was added. After 5 minutes, 50 μL of 0.1 M sodium hydroxide (NaOH, Sigma®) was added. Absorbance was read at 415 nm after 10 minutes at room temperature. The blank was prepared with 70% ethanol. Calibration curves were prepared with quercetin standards. Results were expressed as mg QE per g (quercetin equivalents per gram of sample).

2.7 High-performance liquid chromatography (HPLC)

Phenolic and flavonoid compounds were quantified by high-performance liquid chromatography (HPLC) according to Al-Taie[31] with modifications. Extracts were prepared at a concentration of 0.25 g mL^{-1}, macerated in 60% methanol, and filtered through 2.5 μm membranes. An injection volume of 20 μL of each sample was analyzed using an HPLC system equipped with a Phenomenex C18 column (100 × 4.6 mm, 3 μm) at a flow rate of 1.3 mL min^{-1}. The mobile phase consisted of solvent A (0.1% trifluoroacetic acid in deionized water) and solvent B (acetonitrile) under a linear gradient from 0 to 100% B within 10 minutes. Detection was performed at 254, 280, and 360 nm for general spectra, polyphenols, and flavonoids, respectively.

Analytical standards of rutin and caffeic acid (Sigma-Aldrich, Steinheim, Germany) were used for calibration-curve construction and compound quantification. Calibration curves were obtained from seven concentrations ranging from 20 to 200 μg mL^{-1} for caffeic acid and 10 to 500 μg mL^{-1} for rutin. Each concentration was injected in triplicate, and linear regression equations were determined from the relationship between peak area and concentration. Results were expressed as mg CAE per g (caffeic acid equivalents) and mg RE per g (rutin equivalents) of sample.

2.8 Statistical analysis

Data on proximate composition and chemical composition were analyzed using R software (The R Foundation for Statistical Computing). The significance level was set at 5% ($p < 0.05$). Data were expressed as mean ± standard deviation and subjected to analysis of variance (ANOVA) to test for significant differences among groups. When significant differences were detected, Tukey's HSD (Honestly Significant Difference) test was applied for multiple mean comparisons. Means not statistically different were grouped by letters according to standard conventions.

Pearson's linear correlation coefficient (r) was calculated to evaluate the relationships among antioxidant activities (ABTS, DPPH, and FRAP), total phenolic content, and total flavonoid content ($p < 0.05$). Statistical analyses were performed using the agricolae package in R. Correlations were interpreted numerically to determine associations between variables.

3. Results and discussion

3.1 Proximate composition of edible flowers

The proximate composition provides fundamental information on the nutritional profile of edible flowers and highlights the heterogeneity among species. The results for the thirteen evaluated samples are summarized in Table 1, which allows a comparative overview of moisture, carbohydrates, proteins, lipids, and ash on a fresh weight basis.

Regarding carbohydrates, *P. volubilis* exhibited the highest content (31.56 ± 0.75%), being statistically superior to the other samples, whereas *T. fruticosum* showed the lowest value (1.45 ± 1.10%). Carbohydrates constituted the major macronutrient fraction after moisture in most samples, reflecting the

Table 1 Proximate composition (%) of ornamental and edible flowers on a fresh weight basis[a]

Flowers	Carbohydrates	Ash	Lipids	Proteins	Moisture
B. glabra (bracts)	14.08 ± 0.90^{c}	1.94 ± 0.07^{bc}	1.00 ± 0.38^{cd}	6.77 ± 0.89^{a}	76.50 ± 0.57^{g}
B. glabra (flower)	17.59 ± 1.64^{b}	2.51 ± 0.41^{ab}	1.31 ± 0.45^{bc}	6.40 ± 1.11^{a}	71.46 ± 0.63^{h}
M. paniculata	4.00 ± 0.54^{hi}	2.82 ± 0.21^{a}	0.48 ± 0.03^{def}	3.73 ± 0.28^{cd}	89.04 ± 0.98^{b}
A. megapotamicum	11.16 ± 0.85^{cdef}	1.59 ± 0.29^{cd}	0.79 ± 0.09^{cde}	3.66 ± 0.15^{cde}	82.89 ± 0.90^{de}
A. purpurata (bracts)	10.22 ± 0.24^{def}	2.70 ± 0.18^{a}	0.83 ± 0.15^{cde}	0.92 ± 0.14^{h}	85.33 ± 0.30^{cd}
A. leptopus	11.76 ± 2.30^{cde}	2.60 ± 0.50^{ab}	0.62 ± 0.13^{def}	3.71 ± 0.24^{cde}	81.38 ± 1.56^{ef}
A. pintoi	4.14 ± 0.67^{hi}	2.87 ± 0.17^{a}	0.64 ± 0.12^{def}	2.38 ± 0.13^{efg}	89.90 ± 0.71^{b}
I. coccinea	13.02 ± 0.81^{cd}	0.93 ± 0.09^{de}	0.12 ± 0.02^{f}	1.05 ± 0.15^{gh}	84.89 ± 0.79^{cd}
M. erythrochlamys (bracts)	12.65 ± 0.34^{cd}	0.88 ± 0.22^{de}	2.80 ± 0.15^{a}	5.71 ± 0.25^{ab}	77.84 ± 0.22^{g}
M. erythrochlamys (flower)	13.26 ± 1.63^{cd}	0.84 ± 0.22^{de}	1.92 ± 0.12^{b}	4.95 ± 0.31^{bc}	79.13 ± 1.81^{fg}
P. hortorum	6.23 ± 1.49^{gh}	1.54 ± 0.27^{cd}	0.61 ± 0.23^{def}	1.56 ± 0.25^{fgh}	90.13 ± 0.88^{b}
P. volubilis	31.56 ± 0.75^{a}	3.22 ± 0.24^{a}	0.22 ± 0.13^{ef}	3.08 ± 0.19^{de}	61.99 ± 0.86^{i}
P. auriculata	8.84 ± 0.09^{efg}	1.02 ± 0.10^{de}	0.68 ± 0.01^{def}	3.47 ± 0.48^{de}	86.30 ± 0.10^{c}
T. fruticosum	$1.45 \pm\pm 1.10^{i}$	1.29 ± 0.32^{cde}	0.41 ± 0.08^{def}	3.45 ± 0.26^{de}	93.36 ± 0.72^{a}
T. erecta	8.05 ± 0.45^{fg}	0.54 ± 0.11^{e}	0.82 ± 0.39^{cde}	1.55 ± 0.12^{fgh}	88.98 ± 0.61^{b}

[a] Values are expressed as mean ± standard deviation ($n = 3$). Data were analyzed by one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test for multiple comparisons. Means followed by different letters within the same column differ significantly ($p < 0.05$).

metabolic role of simple sugars such as glucose, fructose and sucrose in floral tissues. Studies on edible flowers including *Bauhinia variegata*, *Gmelina arborea* and *Rosa* spp. report wide ranges of carbohydrate contents, particularly when expressed on a dry-weight basis, reinforcing the wide range of carbohydrate contents reported for edible flowers under different analytical bases and growing conditions.[32–34]

With respect to ash content, *P. volubilis* exhibited the highest value (3.22 ± 0.24%), whereas *T. erecta* presented the lowest (0.54 ± 0.11%). Coyago-Cruz *et al.* (2024)[23] also reported significant variability in the ash content of several species. For *Thunbergia grandiflora*, which belongs to the same genus as some of the samples in this study, they reported a value of 1.85%. For the same species analyzed in the present work (*M. erythrochlamys* and *A. purpurata*), those authors previously reported ash contents ranging from 0.18% to 4.02%. In contrast, our study recorded more specific values: 0.88 ± 0.22% for bracts and 0.84 ± 0.22% for flowers of *M. erythrochlamys*, and 2.70 ± 0.18% for *A. purpurata*. These values are lower than those reported for edible flowers from Thailand, which ranged from 3.28% to 7.08%.[34]

Lipid contents were low in all samples, with the highest value in *M. erythrochlamys* (bracts = 2.80 ± 0.15%) and the lowest in *I. coccinea* (0.12 ± 0.02%). Chensom, Okumura, and Mishima (2019)[35] reported lipid levels between 0.4% and 0.8% in 13 Japanese flowers, whereas Hegde *et al.* (2023)[33] found values from 1.54% to 4.03% in four species from the Western Himalayas. Conversely, Suksathan *et al.* (2021)[34] observed substantially higher levels, ranging from 1.52% to 32.30%. These low lipid contents reflect the metabolic strategy of plants, which prioritize carbohydrates as their main energy source and storage compound, while lipids serve primarily structural and protective roles, predominating only in specific oil-bearing seeds.[36]

For proteins, both the bracts and flowers of *B. glabra* exhibited the highest levels (6.77 ± 0.89% and 6.40 ± 1.11%, respectively), showing no significant difference between them but higher values than most other species. The lowest protein content was recorded in *A. purpurata* (0.92 ± 0.14%). Similarly heterogeneous values were reported by Hegde *et al.* (2023),[33] Mlcek *et al.* (2021),[19] and Chensom *et al.* (2023),[35] ranging from 3% to 13.55% in different edible flowers, confirming the wide variability in protein levels among species.

Finally, moisture represented the most abundant component among the proximate parameters. *T. fruticosum* presented the highest value (93.36 ± 0.72%), whereas *P. volubilis* showed the lowest (61.99 ± 0.86%). Coyago-Cruz *et al.* (2024),[23] when analyzing 34 flowers, observed a similar variation, ranging from 42.04% to 95.74%.

Overall, the results of the proximate analysis are consistent with the literature and indicate substantial variability in the nutritional profiles of edible and ornamental flowers. Environmental factors, including temperature, rainfall, soil characteristics and seasonal conditions, are known to influence the synthesis and accumulation of macronutrients and minerals, contributing to compositional differences among species and growing sites. Recent studies have reported that such environmental variation can affect protein, lipid, carbohydrate and ash contents, resulting in broad natural ranges across floral species.[37–41] Accordingly, comparisons among studies should consider the ecological and environmental context of the analyzed samples.

3.2 Antioxidant activity

Significant differences ($p < 0.05$) were observed among the analyzed flower species in the ABTS, DPPH and FRAP assays, indicating marked variability in antioxidant responses (Table 2). Antioxidant capacity is known to be influenced by multiple factors, including phytochemical composition, extraction conditions and the analytical principle of each assay. Therefore,

Table 2 IC_{50} (μg mL^{-1}) values from ABTS, DPPH, and FRAP assays of flowers[a,b]

Flowers	ABTS/IC_{50}	DPPH/IC_{50}	FRAP/IC_{50}
A. megapotamicum	2.41 ± 0.33^{bc}	3.24 ± 0.24^{d}	0.15 ± 0.06^{bcd}
A. purpurata (bracts)	0.18 ± 0.16^{f}	0.32 ± 0.03^{g}	0.03 ± 0.01^{d}
A. leptopus	0.55 ± 0.01^{f}	0.43 ± 0.00^{fg}	0.14 ± 0.04^{cd}
A. pintoi	2.51 ± 0.05^{b}	4.40 ± 0.34^{c}	0.36 ± 0.05^{bc}
B. glabra (bracts)	0.26 ± 0.07^{f}	0.47 ± 0.03^{fg}	0.07 ± 0.04^{d}
B. glabra (flower)	0.64 ± 0.12^{f}	0.66 ± 0.10^{fg}	0.10 ± 0.07^{cd}
I. coccinea	0.13 ± 0.03^{f}	0.16 ± 0.05^{g}	0.07 ± 0.05^{d}
M. erythrochlamys (bracts)	0.19 ± 0.01^{f}	0.21 ± 0.11^{g}	0.02 ± 0.01^{d}
M erythrochlamys (flower)	0.56 ± 0.11^{f}	1.51 ± 0.02^{e}	0.09 ± 0.01^{d}
M. paniculata	1.40 ± 0.18^{de}	1.61 ± 0.07^{e}	0.10 ± 0.01^{cd}
P. hortorum	0.23 ± 0.06^{f}	0.25 ± 0.10^{g}	0.18 ± 0.02^{bcd}
P. volubilis	1.26 ± 0.04^{e}	0.93 ± 0.25^{f}	0.16 ± 0.06^{bcd}
P. auriculata	0.27 ± 0.02^{f}	0.34 ± 0.22^{g}	0.41 ± 0.11^{b}
T. fruticosum	1.92 ± 0.56^{cd}	11.55 ± 0.08^{b}	0.73 ± 0.28^{a}
T. erecta	1.36 ± 0.11^{e}	3.95 ± 0.40^{c}	0.25 ± 0.08^{bcd}

[a] Values are expressed as mean ± standard deviation of the analyzed flowers. [b] Means followed by the same letter within a column do not differ significantly according to Tukey's test ($p < 0.05$).

the results are discussed comparatively, considering the specific response patterns observed for each method.

This variation is consistent with the literature, which reports wide fluctuations in antioxidant responses depending on species, extraction solvent and analytical method employed. In the present study, *I. coccinea* (0.13 ± 0.03 μg mL^{-1}, ABTS) and *M. erythrochlamys* (0.19 ± 0.01 μg mL^{-1}, ABTS) exhibited the highest antioxidant capacities, followed by *B. glabra* and *A. purpurata*, which showed intermediate responses.

Comparable patterns have been described in studies on edible and ornamental flowers, such as *M. erythrochlamys* (67 mmol TE per g DW), while *A. purpurata* and *Thunbergia* spp. exhibited moderate levels (2–8 mmol TE per g DW). Even when expressed using different analytical units and assay systems, these datasets consistently demonstrate pronounced interspecific variability in antioxidant performance. In this context, species with intense coloration and higher phenolic content tend to exhibit greater antioxidant responses, although numerical discrepancies are expected due to differences in analytical units (μg mL^{-1} *versus* mmol TE per g DW), solvent type and plant tissue analyzed.[23]

The results obtained further reinforce this trend, as *I. coccinea* and *M. erythrochlamys* (bracts) presented the lowest IC_{50} values in the ABTS, DPPH and FRAP assays, indicating higher radical-scavenging and ferric-reducing efficiencies. Previous studies support these findings. Rajayan *et al.* (2024)[42] reported low IC_{50} values in the DPPH assay (249 μg mL^{-1}) for the 70% hydroalcoholic extract of *I. coccinea*, while Chandrasekaran *et al.* (2019),[43] using an aqueous extract of the same species, reported a value of 13.58 μg mL^{-1}, in agreement with the range observed in the present study.

The high antioxidant activity observed may be associated with the presence of anthocyanins such as cyanidin and pelargonidin, compounds widely recognized for their reducing capacity and oxidative stability.[44–46] Conversely, other pigmented flowers such as *B. glabra*, *T. erecta* and *P. volubilis*, although visually intense, exhibited lower antioxidant potential compared with other species, possibly due to the predominance of betacyanins or acylated anthocyanins, which show lower reactivity toward DPPH and ABTS radicals. Thus, coloration, while indicative of phenolic pigment presence, should not be interpreted as an absolute marker of antioxidant capacity and must be evaluated in conjunction with phytochemical composition and environmental factors that modulate floral secondary metabolism.[47,48]

Among the analytical methods applied, the ABTS assay proved to be the most sensitive for detecting differences in antioxidant activity among samples, exhibiting a wide range of IC_{50} values (0.13–3.64 μg mL^{-1}) and statistically significant distinctions even with low standard deviations. This sensitivity reflects the versatility of the ABTS radical, which reacts with both hydrophilic and lipophilic compounds, allowing subtle variations in extract composition to be detected. According to the literature, the ABTS method is generally more sensitive and reproducible than DPPH, showing lower coefficients of variation, improved calibration linearity and greater radical stability, which makes it particularly suitable for complex plant matrices. The DPPH assay exhibited a similar overall trend but with higher dispersion and lower discriminating power, likely due to its preferential interaction with predominantly polar compounds. In contrast, the FRAP assay displayed a narrower response range (0.02–0.73 μg mL^{-1}), being appropriate for estimating total reducing potential but less effective in differentiating subtle interspecific variations.[49–51]

Complementarily, the combined application of the three assays enabled a more comprehensive assessment of antioxidant mechanisms. Correlation analysis revealed a moderate and significant positive relationship between ABTS and DPPH ($r = 0.64$; $p = 0.007$) and between DPPH and FRAP ($r = 0.54$; $p = 0.03$), whereas ABTS and FRAP showed a weak and non-significant association ($r = 0.41$; $p > 0.05$). These results indicate that the assays are not interchangeable, as they reflect

distinct antioxidant mechanisms: ABTS and DPPH are based on electron-transfer reactions, while FRAP measures ferric-reducing power.[52–54]

3.3 Quantification of total phenolic and flavonoid compounds

The mean total phenolic and total flavonoid contents of the analyzed flowers are presented in Table 3.

The highest total phenolic contents were recorded for *B. glabra* (bracts = 21.99 ± 0.87 mg GAE per g DW; flowers = 21.08 ± 0.28 mg GAE per g DW), which differed statistically from most other species. These values indicate a high accumulation of phenolic compounds in *B. glabra*. *T. fruticosum* (19.71 ± 0.62 mg GAE per g DW) and *I. coccinea* (18.26 ± 0.28 mg GAE per g DW) followed within the same statistical group, whereas *T. erecta* (10.64 ± 0.37 mg GAE per g DW) and *M. paniculata* (11.99 ± 0.34 mg GAE per g DW) exhibited the lowest phenolic levels.

Studies on edible and ornamental flowers have reported broad ranges of total phenolic contents across species and botanical groups. For instance, Li *et al.* (2014)[55] analyzed 51 flower species in China and reported values ranging from 0.63 to 35.84 mg GAE per g, including data for *Bougainvillea spectabilis* (6.87 mg GAE per g), and *P. hortorum* (25.68 mg GAE per g). Similarly, Zheng *et al.* (2018)[56] evaluated 65 species and observed phenolic contents between 5.48 and 312.21 mg GAE per g. More recently, Tao *et al.* (2025)[15] described values from 7.77 to 244 hookup mg GAE per g among 50 flower species, illustrating the wide phenolic diversity reported for floral matrices under different analytical conditions.

Total flavonoid contents also differed significantly among species ($p < 0.05$). *B. glabra* again presented the highest values (bracts = 11.32 ± 0.53 mg QE per g DW; flowers = 10.61 ± 0.53 mg QE per g DW), while *T. erecta* showed the lowest flavonoid content (5.74 ± 0.43 mg QE per g DW). Intermediate levels were observed for *P. hortorum* (8.87 ± 0.36 mg QE per g DW) and *A. megapotamicum* (8.10 ± 0.18 mg QE per g DW), reflecting differences in flavonoid accumulation among species.

Previous investigations have also reported wide ranges of flavonoid contents in edible flowers. Zheng *et al.* (2018)[56] described values between 0.67 and 85.31 mg CAE per g, whereas Tao *et al.* (2025)[15] reported concentrations ranging from 0.02 ± 0.01 to 31.13 mg CAE per g, further demonstrating the variability of flavonoid profiles across floral species and analytical approaches.

Correlation analysis revealed a strong and highly significant positive relationship between total phenolic and total flavonoid contents ($r = 0.978$; $p < 0.001$), indicating that increases in flavonoid levels accompany proportional rises in overall phenolic content. In contrast, no significant correlations were observed between TPC or TFC and antioxidant activities determined by ABTS, DPPH and FRAP assays ($p > 0.05$), suggesting that antioxidant performance is influenced not only by total phenolic concentration but also by structural characteristics and relative composition of these compounds.[52,57]

Table 3 Total phenolic (TPC, mg GAE per g DW) and flavonoid (TFC, mg QE per g DW) contents of flowers[a,b]

Flowers	TPC	TFC
A. leptopus	12.29 ± 0.51^{f}	6.82 ± 0.16^{cd}
A. megapotamicum	16.29 ± 0.29^{cd}	8.10 ± 0.18^{bc}
A. pintoi	16.12 ± 0.09^{cde}	8.10 ± 0.09^{bc}
A. purpurata (bracts)	12.08 ± 0.69^{f}	6.81 ± 0.19^{cd}
B. glabra (bracts)	21.99 ± 0.87^{a}	11.32 ± 0.53^{a}
B. glabra (flower)	21.08 ± 0.28^{ab}	10.61 ± 0.53^{ab}
I. coccinea	18.26 ± 0.28^{c}	9.43 ± 0.37^{b}
M. erythrochlamys (bracts)	15.62 ± 0.38^{de}	8.04 ± 0.70^{bc}
M. erythrochlamys (flower)	15.73 ± 0.48^{de}	7.23 ± 0.30^{cd}
M. paniculata	11.99 ± 0.34^{fg}	6.87 ± 0.04^{cd}
P. auriculata	14.19 ± 0.64^{de}	7.43 ± 0.43^{cd}
P. hortorum	17.52 ± 0.41^{cd}	8.87 ± 0.36^{bc}
P. volubilis	14.83 ± 0.04^{de}	7.54 ± 0.47^{cd}
T. erecta	10.64 ± 0.37^{fg}	5.74 ± 0.43^{d}
T. fruticosum	19.71 ± 0.62^{ab}	9.78 ± 0.33^{ab}

[a] Values are expressed as mean ± standard deviation of the analyzed flowers. [b] Means followed by the same letter within a column do not differ significantly according to Tukey's test ($p < 0.05$).

3.4 Identification and quantification of phenolic compounds by HPLC-DAD

The analytical calibration curves showed linear behavior across the evaluated concentration ranges, demonstrating excellent agreement with the regression models. Caffeic acid exhibited an average retention time of 4.32 min, with a regression equation of $y = 7.3041x + 108$ ($R^2 = 0.9929$), whereas rutin presented an average retention time of 4.65 min and a regression equation of $y = 11.086x + 101.41$ ($R^2 = 0.9975$). These values indicate satisfactory linearity ($R^2 \geq 0.99$) and high instrumental reproducibility, confirming the reliability of the HPLC-DAD method for targeted phenolic quantification.

Phenolic compounds were identified through comparison of retention times and UV-vis absorption spectra with authentic reference standards, ensuring chromatographic specificity and analytical stability throughout the runs. The concentrations obtained, expressed as mg per g of dry extract, confirmed rutin and caffeic acid as the main quantified phenolic markers among the evaluated samples (Table 4).

Additional peaks corresponding to catechin, ferulic acid, and chlorogenic acid were detected in some samples, but with correlation coefficients below the acceptable limit ($R^2 < 0.99$) and signal intensities lower than the limit of quantification (<LOQ). These results indicate that such compounds were present only at trace levels, preventing the acquisition of reliable quantitative data. Nevertheless, their detection reinforces both the chemical complexity of the flowers and the sensitivity of the analytical method employed.[58,59]

The wide detection of rutin in 10 of the 13 flower species analyzed is consistent with previous studies describing flavonoids, particularly rutin, quercetin, and their glycosylated derivatives, as predominant constituents of ornamental and edible flowers. The concentrations observed vary depending on the tissue, extraction method, and floral developmental stage but consistently confirm rutin as a recurrent phytochemical and antioxidant marker in HPLC-DAD analyses.[60,61]

Table 4 Quantification of rutin and caffeic acid (mg per g dry extract) in flower samples by HPLC[a,b,c]

Flowers	Rutin (4.40–4.80 min)	Caffeic acid (4.20–4.93 min)
A. pintoi	ND	ND
A. purpurata (bract)	ND	ND
I. coccinea	0.97 ± 0.23[f]	ND
A. leptopus	3.81 ± 0.02[e]	ND
P. volubilis	1.31 ± 0.00[f]	ND
A. megapotamicum	7.09 ± 0.02[c]	ND
T. erecta	5.50 ± 0.00[d]	ND
P. hortorum	2.68 ± 0.07[e]	6.58 ± 0.09[b]
B. glabra (flower)	4.55 ± 0.02[d]	6.7 ± 0.3[b]
B. glabra (bract)	ND	ND
T. fruticosum	5.70 ± 0.05[d]	ND
P. auriculata	8.72 ± 0.10[b]	ND
M. erythrochlamys (bract)	12.95 ± 0.25[a]	ND
M. erythrochlamys (flower)	ND	ND
M. paniculata	ND	7.93 ± 0.05[a]

[a] Values are expressed as mean ± standard deviation (mg per g dry extract). [b] ND = not detected. [c] Means followed by the same letter within a column do not differ significantly according to Tukey's test ($p < 0.05$).

The presence of caffeic acid in three species also agrees with the literature, which recognizes this compound as one of the most frequent hydroxycinnamic acids in flowers, although generally found at lower levels than flavonoids.[62] Caffeic acid often occurs in association with chlorogenic and ferulic acids, contributing to the antioxidant and photoprotective profiles of floral species. Studies have shown that caffeic acid is detectable by HPLC in flowers, with concentrations varying according to solvent and environmental conditions.[63]

The detection of trace compounds such as catechin, chlorogenic acid, and ferulic acid below the quantification limit reflects both the phytochemical complexity of the samples and the instrumental and extraction constraints inherent to low-concentration analytes. These substances are frequently reported as secondary constituents in floral matrices, playing complementary roles in chemical characterization and overall antioxidant contribution. Although detected at trace levels, these findings emphasize the phenolic diversity of the analyzed species and the ability of the HPLC-DAD method to simultaneously detect multiple classes of phenolic compounds.[59,62,64]

3.5 Considerations on diversity and compositional variability

The use of references encompassing large sets of flower species arises from the scarcity of specific studies for several of the species investigated here. Rather than a direct comparison among samples, the purpose is to highlight the chemical and nutritional diversity of ornamental and edible flowers, reinforcing their relevance as sources of bioactive compounds and nutrients. This broad comparative approach, adopted in several studies,[15,55,56,65] situates the present research within a global phytochemical diversity framework, demonstrating that even within a single morphological group, there is extensive compositional and functional variability among species.

The differences observed between this, and other studies, should be interpreted considering the environmental and ecological conditions under which the samples were collected. Factors such as temperature, light intensity, water availability, soil type and fertility, altitude, pollination, and phenological stage directly influence the accumulation of secondary metabolites and the proximate composition.[38,40,41] Therefore, the variation among studies does not reflect methodological inconsistencies but rather the metabolic plasticity of plants in response to environmental conditions, underscoring the importance of integrative and comparative approaches to understanding the full range of floral composition.

4. Conclusions

This study systematically characterized the proximate composition, phenolic and flavonoid contents, antioxidant activity, and selected phenolic markers of thirteen ornamental and edible flower species. The results demonstrated marked interspecific variability across all evaluated parameters, reflecting the heterogeneous chemical and nutritional profiles of these flowers. Several species exhibited relevant antioxidant activity, as evidenced by the ABTS, DPPH, and FRAP assays, in association with higher total phenolic and flavonoid contents. The targeted HPLC-DAD analysis confirmed the presence of rutin and caffeic acid as major quantified phenolic compounds in a subset of the evaluated species, contributing to the antioxidant responses observed.

Overall, the findings confirm that ornamental flowers with edible potential present measurable antioxidant properties and distinct compositional profiles, based on experimental data. By generating consistent and comparable physicochemical and functional information for species that remain insufficiently documented in the literature, this work contributes to a more robust scientific understanding of edible ornamental flowers

and supports future studies focused on safety evaluation and food-related applications.

Author contributions

Débora Correia Santana: conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft, and visualization. Ana Carolina Bianco Gomes: investigation and data curation in antioxidant assays. Aline Roseiro Carvalho: investigation and data curation in antioxidant and proximate composition analyses. Ana Claudia Hertel Pereira: data interpretation and critical analysis of experimental results. Luis Filipe Faria Verdan: undergraduate research student; assisted in experimental design and initial data organization as part of a scientific initiation project. Layla de Oliveira Lopes: HPLC analyses and method validation. Kariane Rodrigues de Sousa: support across all experimental stages, laboratory assistance, and data curation. Denise Coutinho Endringer and Wanderson Romão: supervision, conceptualization, and writing – review and editing.

Conflicts of interest

The authors declare that there is no conflict of interest.

Data availability

The data used is provided in the manuscript.

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