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Estimation of *Madia sativa* Molina and *Solidago canadensis* L. (Asteraceae Bercht. & J. Presl) Antioxidant Parameters

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Madia sativa Molina and *Solidago canadensis* L. are representatives of Asteraceae with numerous biological activities. This study aimed to evaluate the total polyphenol content (TPC), radical-scavenging activity by the DPPH method (DPPH), and antioxidant activity by the FRAP (FRAP) and ABTS (ABTS) methods of plant extracts of these species. Plant raw material was collected from the experimental plots of the Department of Cultural Flora and natural flora at the M.M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine during the vegetation in 2024–2025. Depending on the growth stage, *M. sativa* ethanol extracts had 21.64–78.11 mg GAE·g^{-1} of TPC, 41.28–65.78 mmol TE·g^{-1} of DPPH, 155.43–254.19 mmol TE·g^{-1} of FRAP, and 1.12–2.51 mmol TE·g^{-1} of ABTS. The *S. canadensis* extracts demonstrated 48.14–159.21 mg GAE·g^{-1} of TPC, 25.11–46.61mmol TE·g^{-1} of DPPH, 104.31–260.15 mmol TE·g^{-1} of FRAP, and 1.76–3.07 mmol TE·g^{-1} of ABTS. Correlation analysis revealed a strong positive relationship between TPC and FRSA (r = 0.974) in *M. sativa* extracts, and between TPC and ABTS (r = 0.861) in *S. canadensis* extracts. The obtained data showed the highest TPC, FRSA, and FRAP values at the budding stage in *M. sativa*, whereas the highest ABTS values were observed at the flowering stage. In contrast, *S. canadensis* showed a more variable pattern, with maximum FRSA and FRAP values at the flowering stage, whereas TPC and ABTS activity peaked at the budding and early developmental stages, respectively. These results can be used for further pharmacological, biochemical investigations, and breeding work.

Keywords: Canada goldenrod, coast tarweed, polyphenol content, DPPH, ABTS, FRAP

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Introduction

Plants of the Asteraceae Bercht. & J. Presl family are widely distributed worldwide, have a long history of use, and have representatives serving as alternative and new crops to address the global challenges facing modern crop production, agriculture, and the food industry (Lee et al., 2024). Members of this family are classified as valuable resource plants, such as medicinal, food, forage, and honey-producing. Furthermore, plant extracts from this family exhibit wound-healing, estrogenic, anti-diabetic, antispermatogenic, antiulcer, trypanocidal, antispasmodic, and anti-inflammatory activities (Achika et al., 2014). Asteraceae plants have been used in traditional and folk medicine since ancient times (Piątkowska et al., 2022). Among plants of this family, *Madia sativa* Molina and *Solidago canadensis* L. are of particular scientific interest as prospective oil plants (Zardini, 1992) and as plant raw materials with significant pharmacological activities (Hrytsyk et al., 2024), respectively.

Madia sativa Molina, common name "madi" or "melosa", is native to the Americas and, along with the other 11 species, belongs to the genus *Madia* Molina. This species is tolerant of poor, degraded soils and is a plant pioneer (Sofrás, 2021). It is an important traditional oil plant of the ancient people of Chile (Tellez et al., 2023). It is an annual plant with 10–90 cm of height, covered by grandular and non-grandular trichomes; with numerous capitula that open every 7–10 days (Celedón-Neghme et al., 2007). *M. sativa* is characterized by a rich content of biologically active compounds of seed oil. Bulgarian samples had seed oil content of 34.2–36.6%, phospholipids in the range of 1.7–2.6%, sterols at 0.3%, and tocopherols in the range of 768–856 $mg \cdot kg^{-1}$. Linoleic and oleic acids were predominant among unsaturated acids, and palmitic and stearic acids were the main saturated fatty acids (Antova et al., 2017).

M. sativa seed oil of Chile samples had the following nutritional value: 10% of moisture, 28.20–31% of crude protein, 26% of crude lipid, 24% of crude fibre, 5.25–6% of ash, 13–15.73% of total carbohydrates, 800–1,041 $mg \cdot 100\ g^{-1}$ of phosphorus (Schmeda-Hirschmann, 1995). *M. sativa* seeds contain 20% lipids by Soxhlet extraction, 29% protein, a high content of monounsaturated acids (84.3%), and 10.1% polyunsaturated acids. The main fatty acids of *M. sativa* seeds from Chile were oleic acid (25.5%) and monoenoic acid (26.4%) (Acevedo et al., 2012). Aerial parts of *M. sativa* produce the labdanes that have antifungal properties against *Phytophthora cinnamomi*, and twenty-one components were identified: terpenes (72.90%), flavonoids (2.11%), lactones (1.05%), fatty acid derivatives (0.84%) (Wollenweber et al., 2003; Díaz et al., 2020).

The investigations of *Solidago* spp. showed high antioxidant, anti-inflammatory, spasmolytic, cytotoxic, and antimicrobial properties of plant extracts (Toiu et al., 2019). *Solidago candensis* L. is native to Canada, Mexico, and the USA. This species is a perennial hemicryptophyte, rhizomatous plant with lanceolate leaves, flowers are golden yellow (Mikeladze and Bolkvadze, 2021). It was introduced to Europe in the 17th century as an ornamental plant, and by the start of the 21st century, this species had become invasive (Poljuha et al., 2024). Due to generative and vegetative propagation, allelopathic activity of root exudates of *S. canadensis* forms dense populations as weeds and invasive plants (Abhilasha et al., 2008; Yuan et al., 2013; Mikeladze and Bolkvadze, 2021). The comparative study of *S. canadensis* and *S. gigantea* flavonoids found the highest rutin content in the extracts of the first species, which positively impacts symbiotic bacteria and stimulates the root system (Likhanov et al., 2021). Tetraploids and hexaploids of *S. canadensis* can form stable communities compared with diploids due to their greater competitive ability, which caused the accumulation of high flavonoid content (Yang et al., 2021). Different plant raw materials of *S. canadensis* contain the terpenoids, phenolic acids (hydroxybenzoic and hydroxycinnamic acids), and flavonoids (flavonols, flavanols, flavanones) (Poljuha et al., 2024).

The study of hexane and ethanol extracts from three *Solidago* species identified numerous volatile components, some of which exhibited antibacterial activity, especially against *Staphylococcus* spp. and *Bacillus subtilis*. The ethanol extracts demonstrated the highest antimicrobial activity compared to the hexane extracts; conversely, the hexane extracts exhibited better mutagenic activity (Kołodziej et al., 2011). The essential oil of *S. canadensis* from different regions of Ukraine contained 75 constituents, among which predominant were sesquiterpenes, and exhibited high antimicrobial activity (Raal et al., 2026).

Since *M. sativa* plants have been studied primarily in terms of the quantitative and qualitative composition of their oil, there is insufficient information regarding the antioxidant status of this plant's raw material. As for *S. canadensis* plants, their antioxidant potential has been studied to some extent, but only during a specific stage of plant development, whereas our study aimed to determine the antioxidant parameters of extracts from selected plants throughout the growing season. In this case, the study investigated the antioxidant

properties of the understudied species *M. sativa* and the invasive *S. canadensis* within the Asteraceae family during vegetation, which may be useful for future pharmacological research and breeding programs.

Material and Methodology

Plant material

Plants were collected randomly (n = 10) from experimental plots (*Madia sativa* Molina) of the Department of Cultural Flora and from natural flora (*Solidago canadensis* L.) of M.M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine at the sprouting, budding, flowering, and seed-ripening stages in 2024–2025. The plant raw material was dried at 45 °C for subsequent extraction and measurement. Biochemical analyses were carried out in triplicate.

Extract preparation

1 g of dried plant raw material (above-ground part) was mixed with 50 mL of 80% ethanol. The mixtures were shaken for 12 hours on the Unimax 2010 horizontal shaker (Heidolph Instrument GmbH, Germany). The obtained samples were filtered via Munktell No. 390 filtering paper (Munktell & Filtrac, Germany).

The total polyphenol content

The polyphenol content of plant extracts was determined by the Folin-Ciocalteu assay (Lachman et al., 2006). The volumetric flask (50 ml) was filled with extract (0.1 ml), and then the Folin-Ciocalteu reagent

Figure 1 *Madia sativa* Molina plants in the experimental collection of the Department of Cultural Flora (Ukraine)

(0.85 ml) was added. After 3 min, add 20% NA_2CO_3 (5 ml). After stirring the mixture, water was added till the mark (50 ml). Experimental flasks were placed in the dark for 2 hours, and then analyzed on a Shimadzu UV-1800 UV/Visible Scanning Spectrophotometer (Shimadzu, Kyoto, Japan) at 765 nm. Gallic acid was used as a standard, and results were expressed as mg GAE·g^{-1}.

DPPH radical scavenging activity

A working DPPH solution 25 mg·L^{-1} was prepared using methanol and 2,2-diphenyl-1-picrylhydrazyl (DPPH) (Sigma Aldrich, USA). DPPH solution (3.9 mL) and plant extract (0.1 mL) were mixed, stirred, and left in the dark for 10 min. The solution was measured at 515 nm against a blank solution, using a Shimadzu UV-1800 UV/Visible Scanning Spectrophotometer (Shimadzu, Kyoto, Japan). Based on the calibration curve, antioxidant activity was expressed as the mmol of Trolox equivalent per gram of dried matter (mmol TE·g^{-1} DW) (Brand-Williams et al., 1995).

ABTS radical scavenging assay

According to Re et al. (1999), the ABTS radical scavenging assay was conducted. Working ABTS solution was created using the ABTS·+ radical cation (2,2'-azinobis-3-ethylbenzothiazoline-6-sulfonic acid) (Sigma Aldrich, USA), potassium persulfate ($K_2S_2O_8$) (Sigma Aldrich, USA), and acetate buffer (pH = 4.3). 3 mL of ABTS solution and 0.05 mL of extract were mixed, stirred, and left in the dark for 20 min. The solution was measured at 734 nm against a blank solution, using a Shimadzu UV-1800 UV/Visible Scanning Spectrophotometer (Shimadzu, Kyoto, Japan). Based on the calibration curve, antioxidant activity was expressed in mmol of Trolox equivalent per gram of dry matter (mmol TE·g^{-1} DW).

FRAP assay

The FRAP assay was used to determine antioxidant activity (Pedersen et al., 2000). FRAP solution was created using 2,4,6-tris(2-pyridyl)-S-triazine (Sigma Aldrich, USA), ferric chloride ($FeCl_3$) (Sigma Aldrich, USA), and acetate buffer (pH = 3.5). 3 mL of working FRAP solution and 0.5 mL of extract were mixed, stirred, and left in the dark for 20 min. The solution was measured at 593 nm against a blank solution, using a Shimadzu UV-1800 UV/Visible Scanning Spectrophotometer (Shimadzu, Kyoto, Japan). Based on the calibration curve, antioxidant activity was expressed as the mmol of Trolox equivalent per g of dried matter (mmol TE·g^{-1}).

Statistical analysis

Results are represented as the mean values of three replications ±standard deviation (SD). The obtained data were analysed with an ANOVA test, and differences between means were compared through the Tukey-Kramer test ($p < 0.05$).

Results and Discussion

Plants that possess medicinal properties and whose raw materials exhibit a wide range of biological activity may demonstrate high antioxidant potential (Zafar et al., 2023). The study of the antioxidant properties of plant materials requires specialized methods for determining antioxidant parameters (Gulcin, 2025). The main factors contributing to the antioxidant activity in medicinal plant materials are polyphenolic compounds (Amsalu and Asfaw, 2020). The content of antioxidants in plant material depends on genetic, physiological, and environmental factors, as well as post-harvest storage (Li et al., 2012). Another equally important factor is the extraction process and the solvent, so some plants exhibit higher levels of antioxidant activity in methanol and ethanol extracts, whilst others do so in acetone extracts (Koc et al., 2014; Lee et al., 2024). Some studies on Asteraceae representatives have shown the presence of valuable polyphenols and high antioxidant activity in methanol (Shahat et al., 2014) and ethanol (Sowa et al., 2020) extracts.

The total polyphenol content of *M. sativa* ethanol extracts was from 21.64 to 78.11 mg GAE·g^{-1}, depending on growth stage (Figure 2). The highest polyphenol content was determined at the budding stage, and the lowest at the seed ripening stage. Free radical scavenging activity of the investigated ethanol extracts was from 41.28 to 65.78 mmol TE·g^{-1}. The maximum value of this parameter is determined at the budding period, and the minimum at the seed ripening, as well as the total polyphenol content.

The increased accumulation of polyphenols during the budding stage may be associated with intensified metabolic activity and the synthesis of secondary metabolites involved in plant defense and reproductive development. In contrast, the decrease observed during seed ripening could be due to a redistribution of metabolic resources toward seed formation and a reduction in phenolic compound biosynthesis.

A comparable range of TPC variation across growth stages has been reported for *Echinacea* species (21.15–78.34 mg GAE·g^{-1}) (Vergun et al., 2024). However, in that case, the maximum accumulation occurred at the flowering stage rather than at the budding stage, indicating species-specific differences in phenolic metabolism dynamics. When compared with other Asteraceae species, the TPC values obtained for *M. sativa* fall within or exceed the ranges reported in the literature. For example, *Helianthus annuus* extracts contained 23.09 mg GAE·g^{-1} (Ye et al., 2015), while *Chrysanthemum indicum* showed 15.0–64.1 mg GAE·g^{-1} depending on origin (Uranishi et al., 2024), and *Artemisia dracunculus* ranged from 19.82 to 47.21 mg GAE·g^{-1} across different locations (Ulewicz-Magulska and Wesolowski, 2023). The relatively high

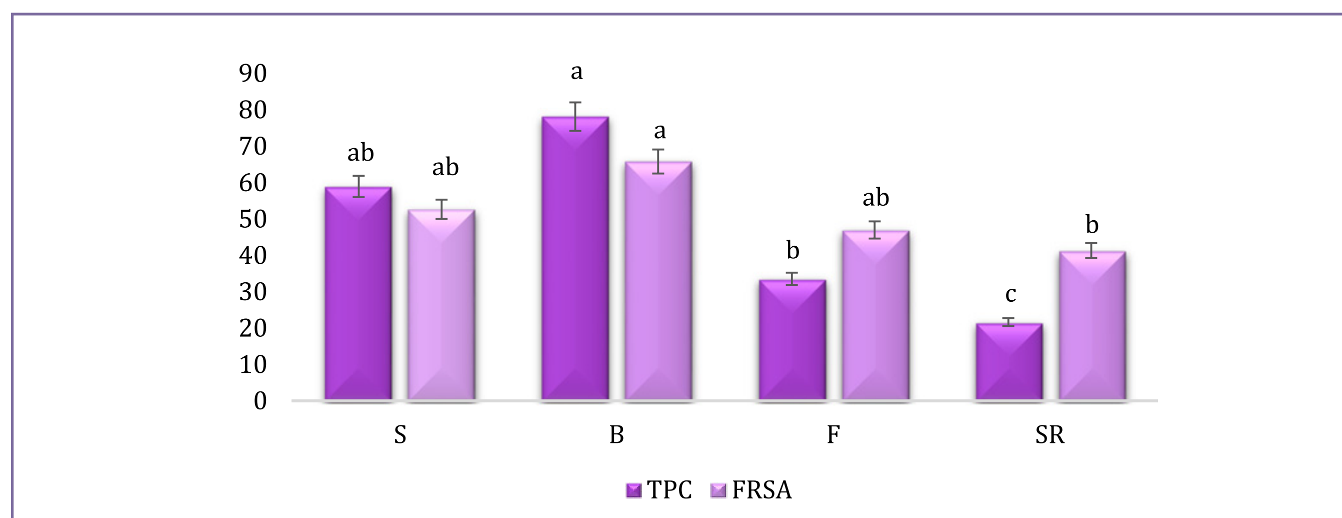

Figure 2 The total polyphenol content and free radical scavenging activity of ethanol extracts of *Madia sativa* Molina during vegetation; TPC – total polyphenol content (mg GAE·g^{-1}); FRSA – free radical scavenging activity (mmol TE·g^{-1}, TE – Trolox equivalent); S – sprouting, B – budding: F – flowering; SR – seed ripening. Means in each column followed by different letters are significantly different ($p < 0.05$)

maximum values observed in *M. sativa* suggest that this species may represent a promising source of polyphenolic compounds. However, these comparisons should be interpreted with caution due to differences in extraction conditions, plant material, and analytical methodologies.

There are currently many methods available for determining antioxidant activity of plant extracts, including DPPH, FRAP, ABTS, etc. (Sadowska-Bartosz and Bartosz, 2022). Ferric reducing antioxidant power (FRAP) is a simple antioxidant assay that measures a sample's ability to reduce a metal complex over incubation time (López-Alarcón and Denicola, 2013).

The antioxidant activity (AA) of *M. sativa* extracts was also measured by the FRAP and ABTS methods (Figure 3). During the seed-ripening period, the AA measured by the FRAP method was minimal (155.43 mmol TE·g^{-1}). At the budding stage, maximal AA was determined using this method (254.19 mmol TE·g^{-1}). AA by the FRAP method decreased from the budding to the seed ripening.

The determination of AA by the ABTS showed the highest value at the flowering stage (2.51 mmol TE·g^{-1}) and the lowest at the seed-ripening stage (1.12 mmol TE·g^{-1}). The increase from sprouting to flowering, followed by a decline, suggests that compounds responsible for ABTS radical scavenging may accumulate differently compared to those contributing to ferric reducing capacity.

The observed differences between FRAP and ABTS results may be explained by the distinct reaction mechanisms of these assays. While FRAP primarily reflects the reducing potential of antioxidants, ABTS evaluates radical scavenging activity and is sensitive to a broader range of compounds, including both hydrophilic and lipophilic antioxidants. Therefore, the shift of maximum activity from budding (FRAP) to flowering (ABTS) may indicate qualitative changes in the composition of antioxidant compounds during plant development.

Previous data on different forage plants, such as *Bidens ferulifolia* (Jacq.) Sweet, *Rhaponticum carthamoides* (Willd.), and *Silphium* spp. (Asteraceae) from the same experimental collection demonstrated high antioxidant potential (Shymanska et al., 2020).

Solidago spp. are known as a plant raw material with high antioxidant activity and valuable polyphenol content (Marksa et al., 2020).

The total polyphenol content (TPC) of *S. canadensis* ethanol extracts ranged from 48.14 to 159.21 mg GAE·g^{-1} depending on the growth stage (Figure 4). The highest values were observed at the budding stage, while the lowest were recorded during seed ripening. In contrast, free radical scavenging activity (FRSA) varied from 25.11 to 46.61 mmol TE·g^{-1} and reached its maximum at the flowering stage rather than budding. This discrepancy suggests that, in *S. canadensis*, antioxidant activity is not determined solely by total polyphenol content but may also depend on qualitative

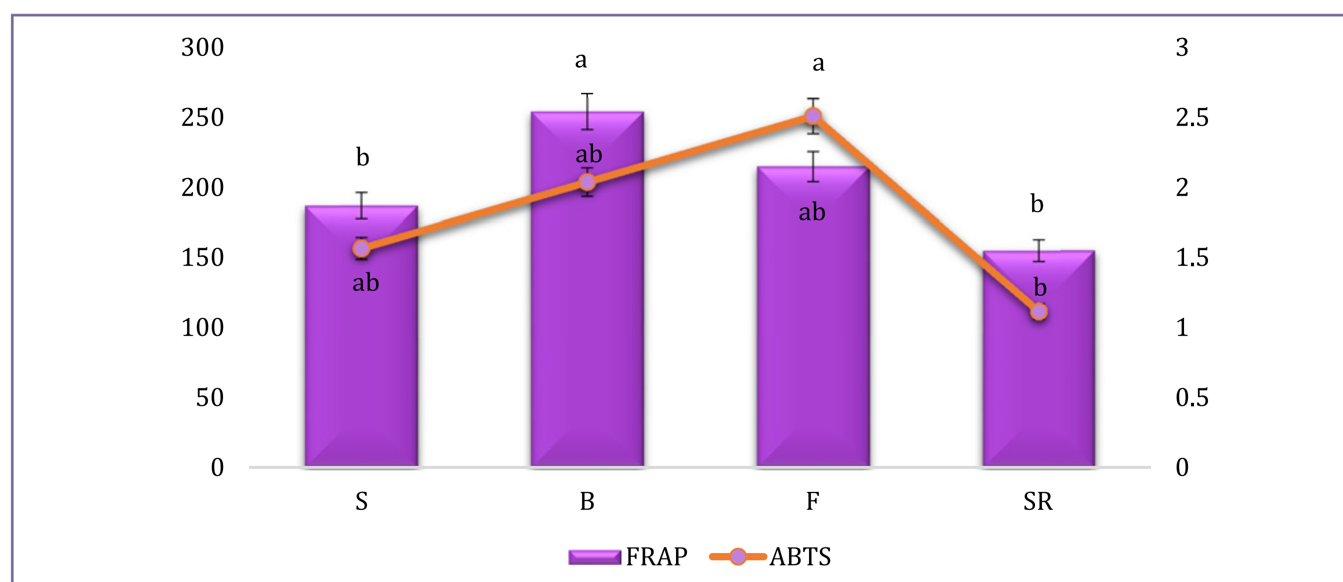

Figure 3 The antioxidant activity by FRAP and ABTS methods of ethanol extracts of *Madia sativa* Molina during vegetation (mmol TE·g^{-1}, TE – Trolox equivalent): S – sprouting, B – budding; F – flowering; SR – seed ripening. Means in each column followed by different letters are significantly different ($p < 0.05$)

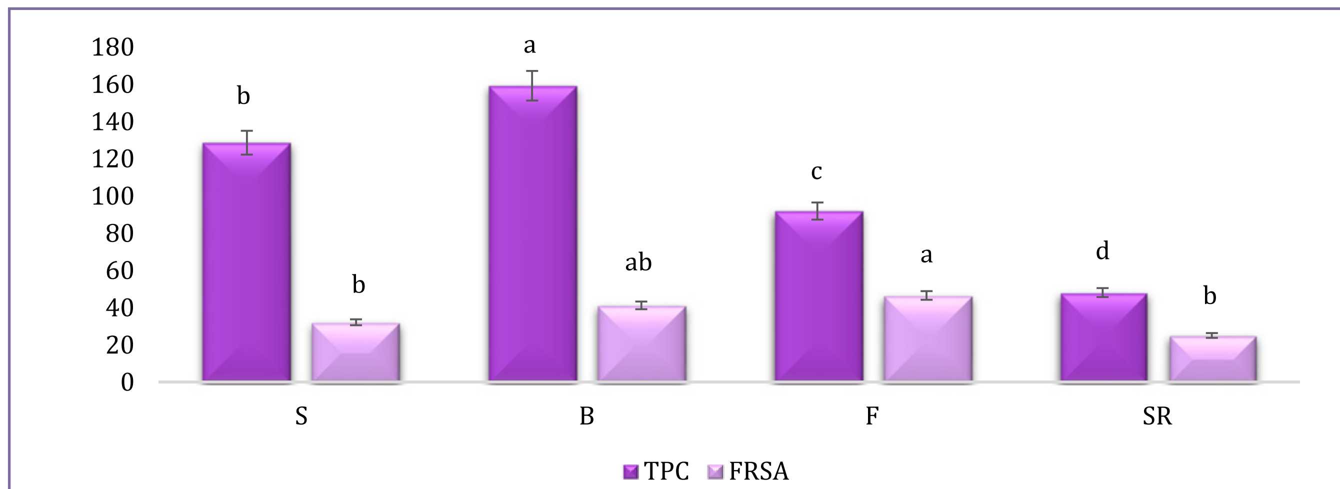

Figure 4 The total polyphenol content and free radical scavenging activity of ethanol extracts of *Solidago canadensis* L. during vegetation; TPC – total polyphenol content (mg GAE·g^{-1}); FRSA – free radical scavenging activity (mmol TE·g^{-1}, TE – Trolox equivalent); S – sprouting, B – budding; F – flowering; SR – seed ripening. Means in each column followed by different letters are significantly different ($p < 0.05$)

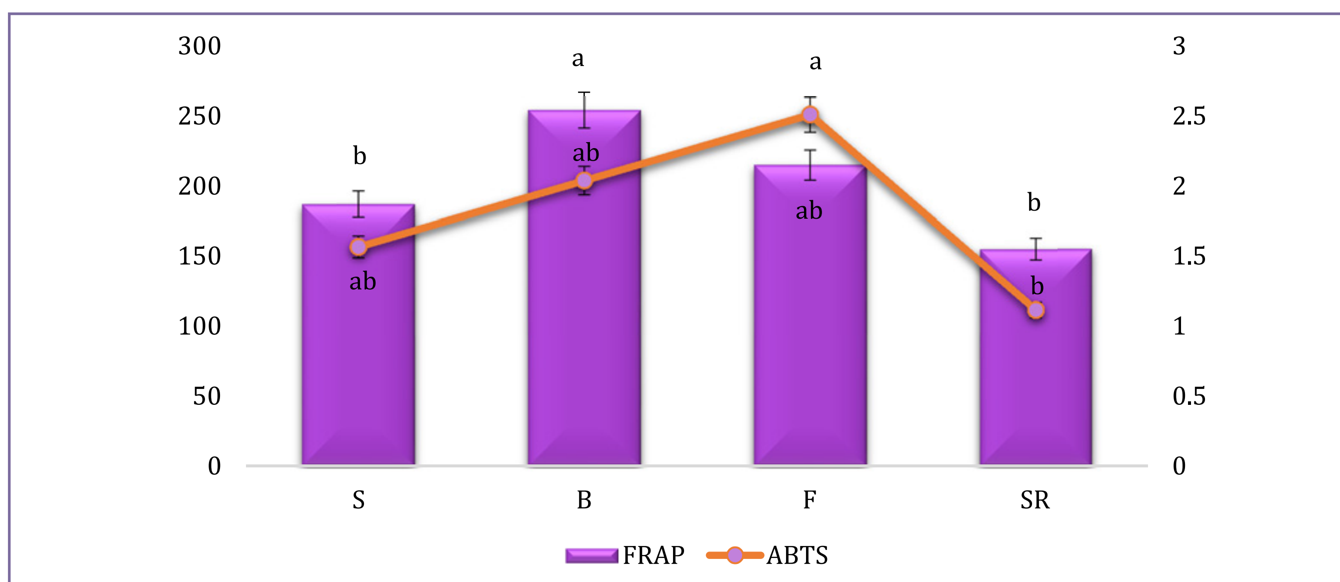

Figure 5 The antioxidant activity by FRAP and ABTS methods of ethanol extracts of *Solidago canadensis* L. during vegetation (mmol TE·g^{-1}, TE – Trolox equivalent): S – sprouting, B – budding; F – flowering; SR – seed ripening. Means in each column followed by different letters are significantly different ($p < 0.05$)

changes in phenolic composition or on the contribution of other antioxidant constituents. The decrease in both TPC and FRSA during seed ripening may be associated with reduced metabolic activity and the reallocation of resources toward reproductive processes. However, the shift in maximal FRSA to the flowering stage indicates that the most active antioxidant compounds are likely synthesized or accumulated at this phase, even if their total concentration is not at its peak.

Comparison with other representatives of the genus *Solidago* shows that the obtained TPC values fall within the broad range reported in the literature. For example, *Solidago graminifolia* demonstrated 18.74–192.69 mg GAE·g^{-1} depending on the solvent used (Toiu et al., 2019), highlighting the strong influence of extraction conditions. Similarly, other studies reported 45.78–110.68 mg GAE·g^{-1} (Božac et al., 2025), confirming that ethanol is an effective solvent for polyphenol extraction.

At the same time, much lower values (2.45–3.8 mg GAE·g^{-1}) have been reported for *S. canadensis* extracts obtained using high-pressure and ultrasound techniques (Deng et al., 2015), which may reflect differences in plant material, extraction methods, or reporting. In contrast, *Solidago virgaurea* showed considerably higher antioxidant parameters, including 200 mg CAE·g^{-1} of polyphenols and high activity in ABTS, DPPH, and FRAP assays (Piątkowska et al., 2022).

Overall, these comparisons indicate that *S. canadensis* is a relatively rich source of polyphenolic compounds within the genus, although direct comparison between studies should be made cautiously due to differences in solvents, plant organs, and analytical approaches.

The antioxidant activity of *S. canadensis* extracts, as determined by FRAP and ABTS assays, ranged from 104.31 to 260.15 mmol TE·g^{-1} and from 1.76 to 3.07 mmol TE·g^{-1}, respectively (Figure 5). The substantially lower values obtained by the ABTS method compared to FRAP indicate differences in the sensitivity of these assays to various groups of antioxidant compounds and further support the importance of using multiple methods to characterize antioxidant capacity.

These findings are generally consistent with previous studies demonstrating strong correlations between polyphenol content and antioxidant activity in Asteraceae species (Paixão et al., 2007; Marius et al., 2016). High correlations between TPC and FRAP, or DPPH ($r > 0.9$), have been reported across multiple taxa, including *Achillea*, *Artemisia*, and *Tanacetum* (Colak et al., 2017). Similarly, strong relationships among ABTS, FRAP, and TPC have been observed in other Asteraceae species, such as *Bubonium imbricatum* and *Cladanthus arabicus* (Aghraz et al., 2018).

However, the variability in correlation patterns observed in the present study highlights that the relationship between polyphenols and antioxidant activity is species-specific and depends on the qualitative composition of bioactive compounds and the analytical method used.

Correlation analysis revealed distinct patterns for the two studied species. In *M. sativa*, a very strong positive correlation was observed between total polyphenol content (TPC) and free radical scavenging activity (FRSA) ($r = 0.974$), indicating that polyphenols are the primary contributors to antioxidant activity in this species (Table 1). Strong correlations were also found between FRSA and FRAP ($r = 0.867$) and between

Table 1 The correlation between the investigated parameters of *Madia sativa* Molina and *Solidago canadensis* L.

Parameters	TPC	FRSA	FRAP	ABTS
		Madia sativa		
TPC	1.000			
FRSA	0.974**	1.000		
FRAP	0.768*	0.867**	1.000	
ABTS	0.272	0.365	0.754*	1.000
		Solidago canadensis		
TPC	1.000			
FRSA	0.491	1.000		
FRAP	-0.486*	0.410	1.000	
ABTS	0.861**	0.464		1.000

Notes: TPC – total polyphenol content: FRSA – free radical scavenging activity by DPPH method: FRAP – antioxidant activity by the FRAP method: ABTS – antioxidant activity by the ABTS method; ** – correlation is significant at the level of 0.01; * – correlation is significant at the level of 0.05

FRAP and ABTS (r = 0.754), suggesting a relatively consistent contribution of antioxidant compounds across different assay systems.

In contrast, *S. canadensis* exhibited a different correlation profile. The strongest relationship was observed between TPC and ABTS (r = 0.861), while a moderate negative correlation was observed between TPC and FRAP (r = -0.486). This indicates that, in this species, antioxidant activity measured by different methods may be influenced by distinct groups of compounds, and that total polyphenol content alone is not a sufficient predictor of antioxidant capacity. The weaker correlations between other parameters further support the complexity of the antioxidant system in *S. canadensis*.

Results obtained across different Asteraceae species showed a strong correlation among antioxidant determination methods, such as DPPH, FRAP, and ABTS (Miler et al., 2026). According to Colak et al. (2017), a very strong correlation between TPC and FRAP (r = 0.934), TPC and DPPH (r = 0.931) was found for 41 Asteraceae species, among which *Achillea* spp., *Artemisia* spp., *Matricaria* spp., *Tanacetum* spp., etc. The Moroccan species *Bubonium imbricatum* Cav. and *Cladanthus arabicus* (L.) Cass. Demonstrated a very strong correlation between ABTS and TPC (r = 0.889 and 0.950, respectively), and between FRAP and TPC (r = 0.945 and 0.808, respectively) (Aghraz et al., 2018).

Conclusions

The results of the study demonstrate that both cultivated *M. sativa* and wild-growing *S. canadensis* are valuable sources of polyphenolic compounds and antioxidant activity, with pronounced variation across growth stages. For *M. sativa*, the budding stage was identified as the optimal period for total polyphenol accumulation and antioxidant activity measured by TPC, FRSA, and FRAP assays, whereas the highest ABTS activity was observed at the flowering stage. In contrast, *S. canadensis* showed a more variable pattern, with maximum FRSA and FRAP values at the flowering stage, whereas TPC and ABTS activity peaked at the budding and early developmental stages, respectively. Overall, the obtained results indicate that the antioxidant potential of both species is strongly influenced by phenological phase, with the most active stages differing between species and analytical methods. The observed correlations between polyphenol content and antioxidant activity further confirm the significant contribution of phenolic compounds, although species-specific differences suggest the involvement of additional bioactive constituents. These findings provide a basis for selecting optimal harvesting periods for both species and may support further pharmacological investigations and the potential use of these plants as sources of natural antioxidants.

Conflict of interest

The authors have no competing interests to declare.

Ethical statement

This article doesn't contain any studies that would require an ethical statement.

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