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RESEARCH ARTICLE

Comparative assessment of active compounds in *Solidago* species from the flora of the Republic of Moldova

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ABSTRACT

Introduction. *Solidago virgaurea* (European goldenrod) and *Solidago canadensis* (Canadian goldenrod) are two plant species that have been extensively investigated for their complex phytochemical profiles, particularly represented by flavonoids, phenolic acids, saponins, and essential oils with notable antioxidant and anti-inflammatory properties.

Material and methods. Goldenrod plants were collected during the flowering period (2019–2024), *S. virgaurea* obtained from spontaneous flora and *S. canadensis* from the Scientific-Practical Center in the Domain of Medicinal Plants of *Nicolae Testemitanu* State University of Medicine and Pharmacy. The macroscopic analysis was performed using specific morphological indices of the *Herba* vegetal product, while the microscopic examination was performed on superficial preparations and cross-sections of vegetal material using a *Micros* microscope equipped with a digital imaging system. Dry extracts were prepared using repeated maceration, followed by phytochemical investigations employing qualitative color and sedimentation tests, ultraviolet-visible spectrophotometry (for total polyphenolic compounds, flavonoids, hydroxycinnamic acids, carotenoids, and saponins), and gas chromatography-mass spectrometry for essential oils. The antioxidant potential was assessed *in vitro* using the 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical scavenging assay and the metal chelation method. *In vivo* pharmacological studies included antimicrobial activity, assessed via serial dilution in liquid nutrient media, and anti-inflammatory activity, evaluated using the xylene-induced ear edema model in mice and the carrageenan-induced paw edema model in rats.

Results. The biological, macroscopic, and microscopic investigations established reliable diagnostic criteria for the clear differentiation and identification of *Herba*-type vegetal products derived from the two *Solidago* species from the Moldovan flora. Qualitative phytochemical screening using specific color and sedimentation reactions confirmed the presence of flavonoids and triterpenic saponins in the examined vegetal products. Quantitative ultraviolet-visible spectrophotometric analysis revealed that *S. canadensis* contained relatively higher levels of bioactive compounds–flavonoids, hydroxycinnamic acids, saponins, and carotenoids–and exhibited greater antioxidant activity compared to *S. virgaurea*. Gas chromatography-mass spectrometry analysis showed that the essential oils of both species differ more quantitatively than qualitatively. Both *Solidago* species exhibited moderate anti-inflammatory and antibacterial activities.

Conclusions. The results of this complex study support the selection of the vegetal product *Solidaginis canadensis herba* as a promising candidate for the local pharmaceutical industry, serving as a valuable source of new local plant-derived antioxidant, anti-inflammatory, and antibacterial drugs.

Keywords: *S. canadensis* L., *S. virgaurea* L., active compounds, pharmacognostic study.

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Key messages

What is not yet known on the issue addressed in the submitted manuscript

Biological, macroscopic, microscopic, phytochemical, and pharma-

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ecological studies of *Solidago* species from the flora of the Republic of Moldova.

The research hypothesis

Solidago virgaurea and Solidago canadensis species from the flora of the Republic of Moldova could serve as sources of various active principles (phenolic compounds, saponins, volatile oils) responsible for important therapeutic effects, such as antioxidant, anti-inflammatory, and antibacterial activities.

The novelty added by manuscript to the already published scientific literature

This is the first detailed study on *S. virgaurea* and *S. canadensis* from the Moldovan flora, providing original data on their pharmacognostic features, chemical composition, and biological activities, while highlighting their potential for future therapeutic applications and local pharmaceutical valorization.

Introduction

The genus *Solidago* L. includes approximately 127 species distributed across all continents. Of these, 105 species are native to Canada and the USA, 9 species occur in Mexico, and 11 species are present in South America, the Azores, Europe, and Asia [1]. In the flora of the Republic of Moldova, *S. virgaurea* (European goldenrod) grows spontaneously, while *S. canadensis* (Canadian goldenrod) is an adventive, cultivated species [2, 3]. According to the "Euro+Med PlantBase" database, in addition to *S. virgaurea*, its subspecies *S. virgaurea* subsp. *taurica* (Juz.) is also found in the wild flora of Moldova [4].

Aerial parts collected from both *S. virgaurea* and *S. canadensis* have been used since ancient times in the treatment of urinary tract diseases (nephrolithiasis, prostate disorders), while the leaves and flowers were employed to obtain natural brown and orange dyes [5, 6].

Although the pharmacotherapeutic potential of these plant species was largely overlooked for a long period, they are currently experiencing renewed interest and recognition within modern phytotherapy [5-7].

European goldenrod and Canadian goldenrod are two species widely studied for their rich phytochemical profiles, particularly in relation to phenolic compounds known for their antioxidant and anti-inflammatory properties [7, 8]. Over the years, research has shown that both species contain significant levels of flavonoids, phenolic acids, saponins, and essential oils (EO), which contribute to their therapeutic applications [9-19]. Key phenolic compounds identified in *S. virgaurea* include rutin, quercetin, isoquercitrin, chlorogenic acid, and dicaffeoylquinic acids, whereas *S. canadensis* also contains high concentrations of similar compounds, with chlorogenic acid and rutin being dominant constituents [12-14]. These phenolics have demonstrated strong antioxidant activity through radical scavenging and metal-chelating assays [7, 12, 15]. In particular, isoquercitrin and chlorogenic acid contribute not only to antioxidant potential but also exhibit anti-inflammatory, cardioprotective, and chemopreventive effects [13-15]. It has been shown that the content and composition of phenolic compounds and EO can be influenced by the plant part analyzed and the extraction method used [16, 17]. These findings support the continued pharmacological interest in *Solidago* species and provide a scientific foundation for their use in herbal medicine and phytotherapy.

It should be noted that phytochemical and pharmacological studies on *Solidago* species from the flora of Moldova have not yet been conducted, although their relevance in the prophylaxis and treatment of urinary tract diseases is evident. Thus, the growing interest in *Solidago* species as medicinal plants, along with the limited research on *S. virgaurea* and *S. canadensis* in our country, served as the motivation for conducting this comprehensive pharmacognostic study.

Material and methods

***Plant material for phytochemical and pharmacological studies*.** Plants of *Solidago* species served as biological material: *S. virgaurea* – collected from the spontaneous flora of the *Trebujeni Landscape Reserve* (47°19′36″N, 28°57′24″E), Orhei district, and *S. canadensis* – from the collection of the Scientific-Practical Center in the Domain of Medicinal Plants (SPCDMP) of *Nicolae Testemitanu* State University of Medicine and Pharmacy (46°54′06″N, 28°40′05″E). Aerial parts of the plants (consisting of fragments of stems, leaves, and inflorescences) collected during the flowering period between 2019 and 2024 were used for this study: *Solidaginis virgaureae herba* and *Solidaginis canadensis herba.* The vegetal products were dried under natural conditions in well-ventilated, dry, and dark rooms and stored in paper bags.

Plant material for macro- and microscopic studies. Fresh and dried plant organs were used: rhizomes and roots, stems, leaves, flowers, and fruits were harvested during the flowering period between 2018 and 2020.

***Dry extract preparation*.** The dried aerial parts were

shredded using a grinder, and the powder was sieved through a 0.5 mm pore sieve. The extracts were obtained by the fractional maceration method with 60% ethyl alcohol for 30 minutes of continuous stirring. The extracts were filtered through Whatman No. 2 paper under vacuum using a Büchner funnel. The same procedure was repeated 5 times until maximum exhaustion. The obtained extracts were concentrated at 40 °C using the Laborota 4011 rotary evaporator [20].

Macro- and microscopic assay. The macroscopic study was based on the following indicators: plant height, rhizome morphology (shape, color, surface, and fracture relief), stem morphology (shape, color, surface, and fracture relief), leaf morphology (type, presence or absence of petiole, arrangement on the stem, leaf size, and lamina configuration), inflorescence morphology (type, size, and color), and fruit morphology (type, shape, and size). The microscopic analysis was conducted on clarified (with chloral hydrate or 3% NaOH) superficial preparations of the leaves and flowers, and on cross-sections of the leaf lamina, stem, and rhizome, using the *Micros* binocular optical microscope at 4x, 10x, and 40x objective magnification [20-22].

Extraction of essential oil (EO). EO were extracted by hydro-distillation using a NeoClevenger extractor from fresh aerial parts (stems, leaves, and inflorescences) collected at the full bloom stage [23].

Qualitative identification of active principles. The qualitative chemical study was performed using color and sedimentation reactions for flavonoids and saponins [20, 24], and the individual components of the EO were identified by gas chromatography-mass spectrometry (GC-MS), comparing the unique mass spectral fragmentation patterns of each peak with the mass spectral computer library database (NIST MS Search 2.2) and relevant references [23, 25].

Spectrophotometric assay of phenolic compounds. The ultraviolet-visible (UV-VIS) spectrophotometric analysis of total polyphenolic compounds, flavonoids, and hydroxycinnamic acids in the dry extracts of *Solidago* species was carried out using the Metertech UV/VIS SP 8001 spectrophotometer. The total content of polyphenols was determined by 2 Folin-Ciocalteau methods (FC1 and FC2), expressed in terms of gallic acid at 760 nm [26, 27]. The flavonoid content was determined relative to rutin after a reaction with aluminium chloride at 412 nm [28]. The quantitative determination of hydroxycinnamic acids was performed relative to caffeic acid after a reaction with Arnow's reagent (sodium molybdate and sodium nitrite) at 500 nm [24]. was All experiments were repeated three times for statistical validity.

Spectrophotometric assay of saponins. The total saponin content was determined using the vanillin-sulfuric acid assay in correlation with a standard saponin solution at 540 nm [29].

Spectrophotometric assay of carotenoid pigments. The total carotenoid content was measured at a wavelength of 448 nm [30].

GC-MS of EO. The obtained EO were diluted in hexane (1:100) and analyzed using an Agilent Series GC-MS system, consisting of a GC 7890B gas chromatograph and an MS 5977A mass spectrometer. The capillary column used was HP-5MS Ultra Inert (30 m x 0.25 mm x 0.25 μm). The temperature program was: 50 °C for 8 min, then heated to 280 °C at 4 °C/min. The carrier gas was helium (1 mL/min), and the injection volume was 3 μL with a 50:1 split ratio [23, 25].

Antioxidant activity. To assess antioxidant activity, two complementary *in vitro* chemical methods were used: ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) assay and the Ferrozine Test (assay of iron-binding antioxidant capacity) [31].

Anti-inflammatory activity. The anti-inflammatory activity of *Solidago* extracts was evaluated in mice using a xylene-induced ear edema model and in rats using a carrageenan-induced paw edema model. Data were analyzed by one-way ANOVA with Bonferroni post-hoc test [32].

Antibacterial activity. The antibacterial activity was determined using the serial dilution method in liquid nutrient medium (2% peptone meat broth, pH = 7.0). *Staphylococcus aureus* (t. 209, ATCC 25923), *Enterococcus faecalis* (ATCC 19433), *Escherichia coli* (ATCC 25922), *Klebsiella pneumoniae* (ATCC 3534/51), and *Pseudomonas aeruginosa* (ATCC 27853) were used as reference cultures [33].

Statistical analysis. All tests were performed in triplicate, and statistical processing of the obtained data was carried out using MS Excel 2021. Variational statistics were applied to calculate the arithmetic mean **±** standard deviation (SD).

Results

Macro- and microscopic study

Species of the genus *Solidago* share common characteristics: they are rhizomatous perennials that develop simple, alternate, ovate-lanceolate leaves with entire blades. The plants form calathidia clustered in simple or paniculate racemes, with ligulate, yellow, female, marginal flowers, while the central ones are tubular and bisexual. The fruits are cylindrical achenes provided with a pappus formed of seriate bristles [2, 8, 10]. At the same time, there are also distinctive morphological criteria for each species. The main specific macroscopic characters for the differentiated identification of vegetal products of the analysed *Solidago* species were established using dried, shredded aerial parts (fragments of stems, leaves, inflorescences, and separated flowers), according to several criteria, as illustrated in the following table (Table 1) [2, 22].

Microscopic techniques were used to identify the main anatomical features, and specific chemical reagents were applied to highlight the structural composition. Based on these observations, the most relevant microscopic characters were selected to ensure the reliable identification of *Solidaginis virgaureae herba* and *Solidaginis canadensis herba* (Table 2) [21, 22]. This anatomical study revealed distinct structural markers that serve as key diagnostic traits for differentiating *S. virgaurea* and *S. canadensis* within the flora of Moldova.

Table 1. Specific macroscopic characters for vegetal products of *Solidago* species

Specific macroscopic characters *Solidaginis virgaureae herba* *Solidaginis canadensis herba*			Vegetal product	
Stem	Cross-section contour		pentagonal	circular
	Color	External surface	light green	dark green
		Internal surface	whitish-green	light green
	Diameter, cm		0.5-1.0	0.4-0.7
Leaf	Shape		ovate-elliptic, toothed margin	elongated-lanceolate, serrate margin
	Color		light green	dark green
	Size (cm)	Length	0.8-1.2	0.9-2.2
		Width	0.2-0.5	0.2-0.3
Inflorescence	Type		erect raceme + calathidium	pyramidal raceme + calathidium
	Calathidium diameter (cm)		1.0-1.5	0.5-0.6
Flower length	Ligulate		0.8-1.2	0.3-0.5
	Tubular		0.2-0.3	0.2-0.4

Table 2. Specific microscopic characters of vegetal products for *Solidago* species

Specific microscopic characters *Solidaginis virgaureae herba*		Vegetal product *Solidaginis canadensis herba*	
Stem	Cross-section contour	pentagonal	circular
	Secretory tissue	secretory channels	secretory channels
Leaf blade	Anatomical type	dorsoventral mesophyll; amphistomatic leaf	equifacial mesophyll; amphistomatic leaf
	Epidermis	▪ well-defined cells; ▪ anomocytic stomata; ▪ multicellular protective conical trichomes; ▪ flabelliform trichomes; ▪ unicellular secretory trichome	▪ well-defined cells; ▪ anomocytic stomata; ▪ multicellular protective conical trichomes; ▪ flabelliform trichomes; ▪ multicellular secretory trichomes
Ligulate/tubulate flowers	Epidermis	rectangular cells with thin walls	rectangular cells with thin walls
	Pappus	multiseriate, non-branched bristles	multiseriate, branched bristles

Phytochemical studies

Qualitative analysis of active compounds. The qualitative comparative analysis of flavonoids and saponins were carried out using specific color and sedimentation reactions, with the observation of characteristic analytical effects, as summarized in the tables below (Table 3) [18, 19].

Table 3. Qualitative comparative analysis of flavonoids and saponins in *Solidaginis virgaureae herba* and *Solidaginis canadensis herba*

Qualitative analysis of flavonoids					
No	Vegetal product	Shinoda test (Zn + HCl solution)	NaOH solution (10%)	Lead acetate solution (2%)	Vanillin solution (1%) in concentrated HCl
1	*Solidaginis virgaureae herba*	pale-pink strong effervescence	yellow-orange, weak precipitate	yellowish-white precipitate	green color, intensity decreases
2	*Solidaginis canadensis herba*	pale-pink, weak effervescence	yellow-orange, weak precipitate	yellowish-white opalescence	yellow color, intensity decreases

Qualitative analysis of saponins						
No	Vegetal product	Foaming reaction		Lead acetate solution	Liebermann-Burchard test	Lafon test
		HCl solution	NaOH solution			
1	*Solidaginis virgaureae herba*	moderate foam	intense foam	white-pink precipitate	negative reaction	dark greenish-blue color
2	*Solidaginis canadensis herba*	moderate foam	intense foam	yellowish opalescence	negative reaction	dark greenish-blue color

Note: *The table illustrates the specific analytical effects observed in identification reactions for flavonoids and saponins in the vegetal products Solidaginis virgaureae herba and Solidaginis canadensis herba. Abbreviation: No – number.*

Gas chromatography-mass spectrometry analysis of EO extracted from fresh aerial parts of *Solidago* species revealed the presence of 51 chemical constituents in the essential oil of *S. canadensis* and 37 components in that of *S. virgaurea* (Fig. 1). The compounds common to both *Solidago* EO include: α-pinene, camphene, sabinene, β-pinene, β-myrcene, limonene, trans-β-ocimene, terpinolene, borneol, bornyl acetate, γ-elemene, β-elemene, β-caryo-

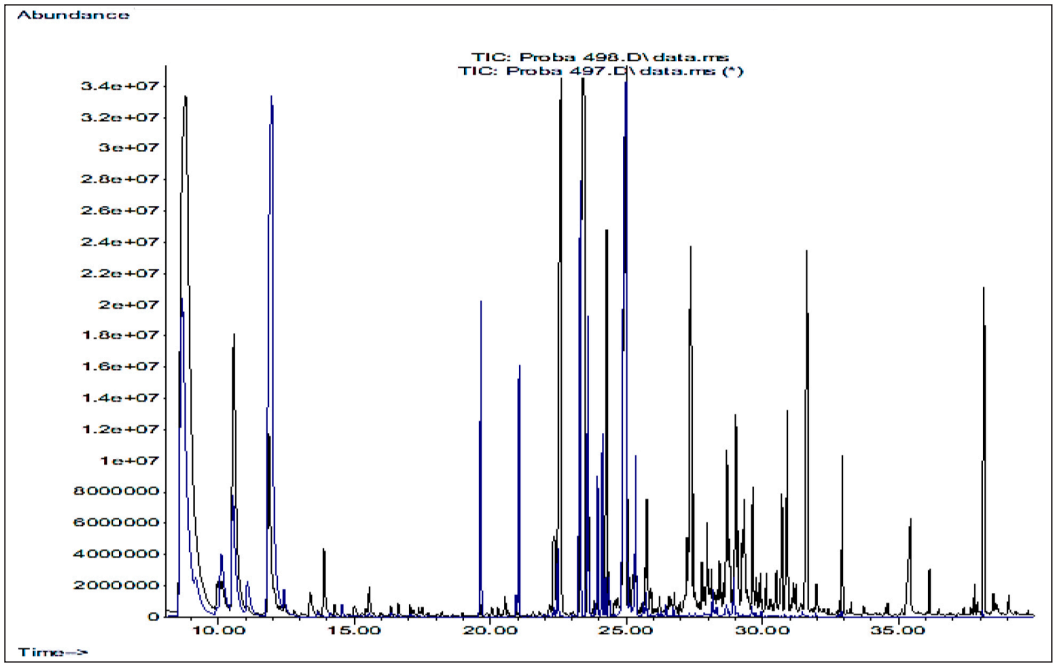

Fig. 1 Chromatogram of *S. canadensis* (sample 497*)* and *S. virgaurea* (sample 498) EO.

Note: *The chromatogram shows the peaks of the separated compounds from the EO of S. canadensis (blue color) and S. virgaurea (black color).*

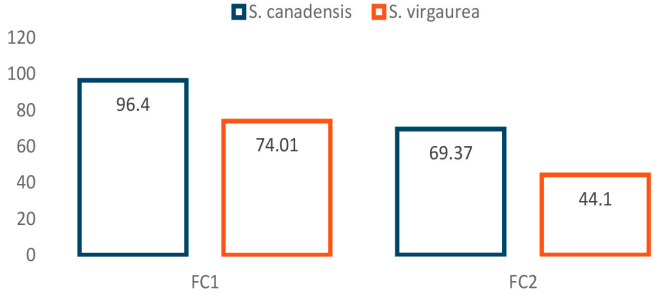

Fig. 2 The total content of polyphenols in *Solidago* extracts by two Folin-Ciocalteu (FC1 and FC2) techniques (mg GAE/g DW).

Note: *The diagram represents the total phenolic content expressed in mg GAE/g DW in Solidago extracts; the blue columns – S. canadensis, the orange ones – S. virgaurea. Variational statistics were applied using MS Excel 2021, and the presented data represent the arithmetic mean of 3 determinations; standard deviations (SD) are as follows: S. canadensis (FC1) – 0.0028; S. virgaurea (FC1) – 0.00047; S. canadensis (FC2) – 0.0010; S. virgaurea (FC2) – 0.00057.*

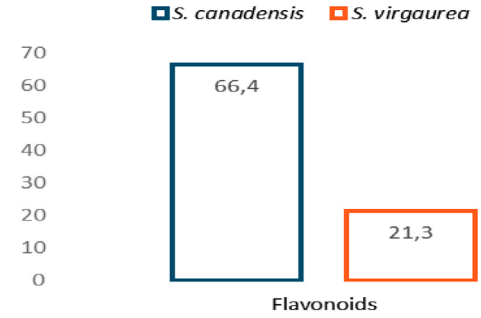

Fig. 3 Total flavonoid content in *Solidago* extracts (mg RE/g DW).

Note: *The diagram represents the total flavonoid content expressed in mg RE/g DW in Solidago extracts.Blue columns – S. canadensis, orange columns – S. virgaurea. Variational statistics were performed using MS Excel 2021. Data represent the arithmetic mean of 3 determinations. Standard deviations (SD) are: S. canadensis – 0.0256; S. virgaurea – 0.0425.*

phyllene, aromadendrene, α -humulene, γ-muurolene, germacrene D, caryophyllene oxide, and phytol. In contrast, some compounds were species-specific, with linalool detected only in *S. canadensis* EO and geraniol identified exclusively in *S. virgaurea* EO (Table 4).

Quantitative analysis of active compounds. The total content of polyphenols in *Solidago* extracts was determined by 2 Folin-Ciocalteau techniques (FC1 and FC2). There are significant differences between the extracts of the analyzed species and between the FC method techniques, in terms of total polyphenol content (FC1: *S. virgaurea* – 74.01, *S. canadensis* – 96.40 mg GAE/g DW; FC2: *S. virgaurea* – 44.10, respectively *S. canadensis* – 69.37 mg GAE/g DW). In the dry extracts of *S. canadensis*, the values of total polyphenol content by both FC techniques are higher than in *S. virgaurea*. The FC1 technique allowed the quantification of a higher concentration of polyphenols for both *Solidago* species (Fig. 2).

The spectrophotometric determination of flavonoids (Fig. 3), in terms of rutin (RE), revealed a higher content of flavonoids in the dry extract of *S. canadensis* (66.4 mg RE/g DW) compared to that of *S. virgaurea* (21.3 mg RE/g DW*)* [34].

The comparative total content of hydroxycinnamic acids (HA), determined by the Arnow spectrophotometric method and expressed as caffeic acid equivalents, showed a concentration of 27 g/100 g DW for the *S. canadensis* extract and 12 g/100 g DW for the *S. virgaurea* extract (Fig. 4) [35].

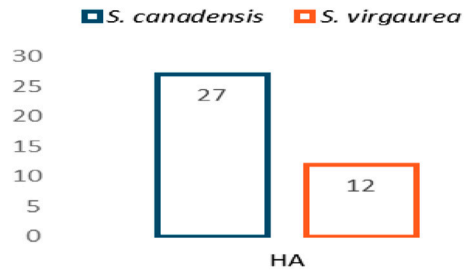

Fig. 4 Total content of HA in *Solidago* extracts (g/100 g DW).

Note: *The diagram represents the total HA content expressed in g/100 g DW in Solidago extracts. Blue columns – S. canadensis, orange columns – S. virgaurea. Variational statistics were performed using MS Excel 2021. Data represent the arithmetic mean of 3 determinations. Standard deviations (SD) are: S. canadensis – 0.0146; S. virgaurea – 0.0049.*

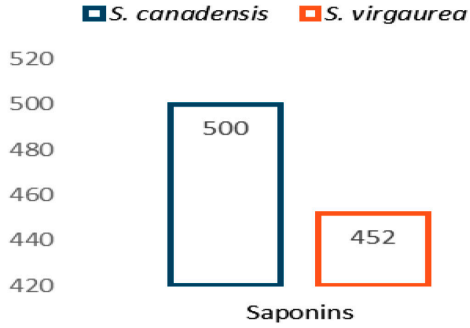

Fig. 5 Total content of saponins in *Solidago* extracts (mg SE/g DW).

Note: *The diagram represents the total saponin content expressed in mg SE/g DW in Solidago extracts. Blue columns – S. canadensis, orange columns – S. virgaurea. Variational statistics were applied using MS Excel 2021, and the presented data represent the arithmetic mean of 3 determinations. Standard deviations (SD) are as follows: S. canadensis – 0.00057; S. virgaurea – 0.00069.*

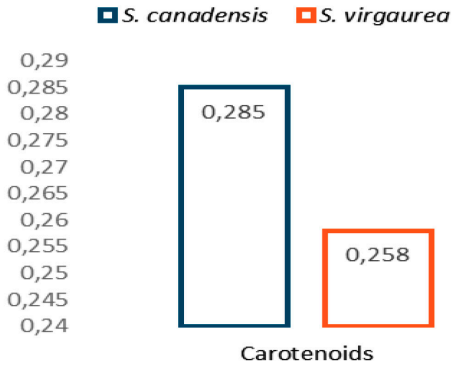

Fig. 6 Total content of carotenoids in *Solidago* extracts (mg βCE/g DW).

Note: *The diagram represents the total carotenoid content in Solidago extracts expressed in mg βCE/g DW. Blue columns – S. canadensis, orange columns – S. virgaurea. Variational statistics were calculated using MS Excel 2021. Data represent the arithmetic mean of 3 determinations. Standard deviations (SD) are: S. canadensis – 0.00054; S. virgaurea – 0.00071.*

Comparative quantitative analysis of saponins (Fig. 5) showed that the dried extract of *S. canadensis* aerial parts contains a higher saponin content (500 mg SE/g DW) compared to the extract of *S. virgaurea* aerial parts (452 mg SE/g DW) [34, 36].

For the spectrophotometric determination of carotenoid pigments (Fig. 6), the following values were obtained: *S. canadensis* – 0.285 mg βCE/g DW, and *S. virgaurea* – 0.258 mg βCE/g DW [34].

Concerning the EO composition of the analyzed *Solidago* species, some compounds were common to both species but different in concentration (Table 4). In *S. virgaurea*, the predominant compound was α-pinene (28.8%), followed by β-caryophyllene (9.96%), β-elemene (8.29%), germacrene D (7.49%), β-myrcene (6.2%), caryophyllene oxide (4.24%), limonene (3.06%), and α-humulene (3.01%). Conversely, the EO of *S. canadensis* was mainly composed of limonene (22.81%), with other major constituents including germacrene D (19.73%), α-pinene (19.03%), β-caryophyllene (6.53%), β-myrcene (4.75%), β-ylangene (4.4%), and bornyl acetate (3.81%) (Table 4).

Table 4. Major chemical constituents in *S. canadensis* and *S. virgaurea* essential oil (EO) analyzed by gas chromatography-mass spectrometry (GC-MS).

No	Compounds	*Solidago canadensis*		*Solidago virgaurea*	
		RT (min)	EO (%)	RT (min)	EO (%)
1	α-Pinene	8.672	19.03	8.672	28.80
2	Camphene	9.163	2.28	na	0.00
3	Sabinene	9.947	0.24	9.947	0.49
4	β-Pinene	10.133	2.66	10.117	0.87
5	β-Myrcene	10.529	4.75	10.529	6.20
6	Limonene	11.972	22.81	11.861	3.06
7	trans-β-Ocimene	12.408	0.67	12.408	0.24
8	Terpinolene	13.645	0.10	13.645	0.07
9	linalool	14.105	0.06	-	0.00
10	Borneol	16.347	0.08	16.347	0.11
11	Geraniol	-	0.00	18.608	0.02
12	Bornyl acetate	19.656	3.81	19.656	0.10
13	γ-Elemene	20.938	0.25	20.938	0.08
14	β-Eiemene	22.485	0.80	22.610	8.29
15	β-Caryophyllene	23.309	6.53	23.447	9.96
16	Aromandendrene	24.117	1.96	24.117	0.73
17	a-Humulene	24.244	0.38	24.244	3.01
18	γ-Muurolene	24.350	0.51	24.350	0.32
19	Germacrene D	24.968	19.73	24.968	7.49
20	Caryophyllene oxide	27.303	0.05	27.357	4.24
21	Phytol	38.084	0.07	38.146	2.66

Note*: The table represents the retention time (RT) expressed in minutes (min) and EO content, expressed in percentage (%), of the main compounds separated by GC-MS from S. canadensis and S. virgaurea EO. The abbreviations used in the table are as follows: No – number, RT – retention time, EO – essential oil, min – minutes.*

Biological activities

The antioxidant activity (Fig. 7) determined by the ABTS assay revealed that leaf extracts from both *Solidago* species exhibited the highest antioxidant activity (44.17 μM TEAC

for *S. canadensis* and 34.31 µM TEAC for *S. virgaurea*), followed by extracts from the aerial parts (39.32 µM TEAC and 33.25 µM TEAC, respectively), and then flower extracts (35.37 µM TEAC for *S. canadensis* and 30.92 µM TEAC for *S. virgaurea*). A comparative analysis using the iron-chelation antioxidant capacity assay showed minimal variation in the results for *S. canadensis* plant materials: the highest chelating ability was observed in the leaves (81.49%), followed by aerial parts (80.19%) and flowers (79.65%). A similar pattern was observed for *S. virgaurea*, with the highest activity in the leaves (80.19%), followed by aerial parts (79.55%) and flowers (79.01%) [34, 37].

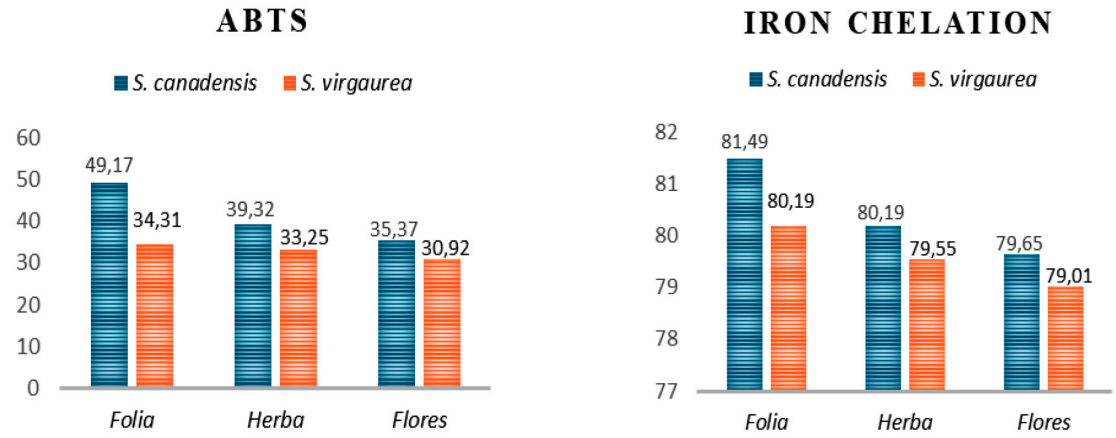

Fig. 7 Comparative antioxidant activity of dried extracts of *S. canadensis* and *S. virgaurea*, determined by ABTS method (µM TEAC) and iron-chelation test (%).

Note: *The diagram represents the comparative antioxidant activity of Solidago extracts (Folia – leaves, Herba – aerial parts, and Flores – flowers) using 2 in vitro methods (ABTS method, expressed in µM TEAC, and iron-chelation test, expressed in %), respectively: the blue columns – S. canadensis, the orange columns – S. virgaurea. Variational statistics were applied using MS Excel 2021, and the presented data represent the arithmetic mean of 3 determinations; standard deviations (SD) 2%.*

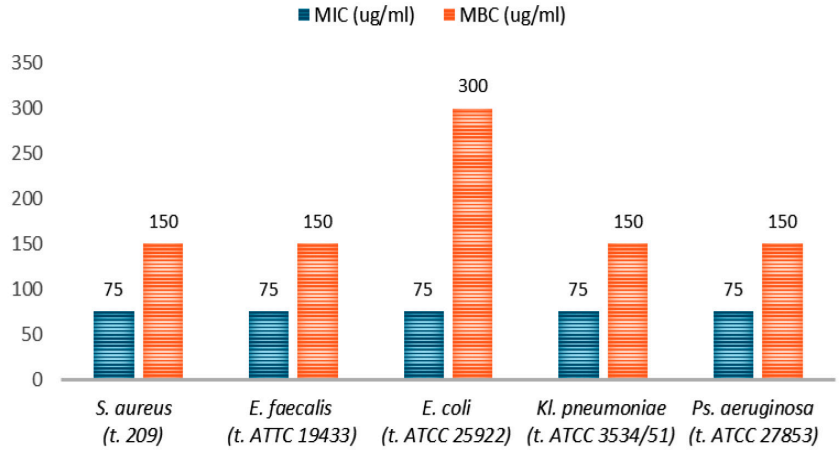

Fig. 8 Antibacterial activity of *S. virgaurea* extract (MIC (µg/ml) – minimum inhibitory concentration, MBC (µg/ml) – minimum bactericidal concentration).

Note: *The diagram represents the antibacterial activity of S. virgaurea extract on different bacterial strains (S. aureus, E. faecalis, E. coli, K. pneumoniae, P. aeruginosa). The blue columns show MIC, expressed in µg/ml, while the orange ones – MBC, expressed in µg/ml.*

The study of the anti-inflammatory activity of *Solidago* aerial parts extracts in the xylene-induced ear edema model in mice showed that, although insignificant compared to the control group, both diclofenac and *Solidago* extracts decreased xylene-induced ear edema. The decrease in edema was more evident with the use of the non-steroidal anti-inflammatory drug and less pronounced with the use of the investigated extracts. The percentage of edema inhibition with diclofenac was 20.38%, and with *Solidago* extracts – 11.99%. When evaluating the anti-inflammatory action of *Solidago* extracts in carrageenan-induced paw edema in rats, a tendency to decrease paw volume compared to the control group was observed, but it was not significant [19, 34].

Determination of the antibacterial activity of *Solidago* extracts was carried out by the serial dilution method in liquid nutrient medium. It was found that the bacteriostatic activity of the *S. virgaurea* aerial parts extract is within the concentration range of 75 µg /ml, and the bactericidal activity varies within the concentration range of 150–300 µg/mL, constituting against *S. aureus* (t. 209), *E. faecalis* (ATCC 19433), *P. aeruginosa* (ATCC 27853), and *K. pneumoniae* (ATCC 3534/51) – 150 µg/ml, and against *E. coli* (ATCC 25922) – 300 µg/mL (Fig. 8).

The bacteriostatic activity of the *S. canadensis* aerial parts extract varies within the concentration range 75 µg/ml – 150 µg/ml and constitutes against *P. aeruginosa* (ATCC 27853) – 75 µg /ml, and against the other investigated bac-

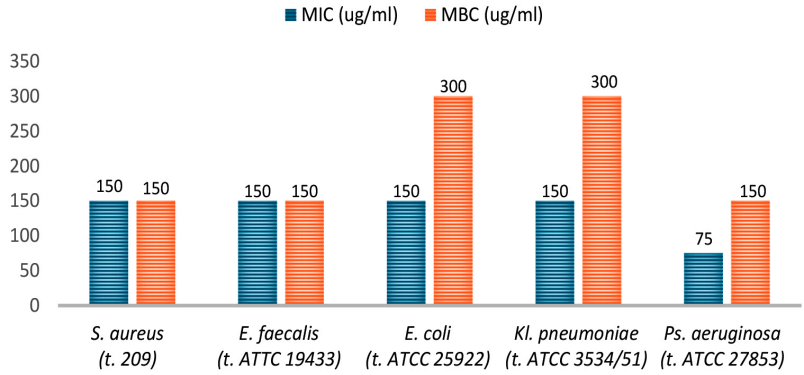

Fig. 9 Antibacterial activity of *S. canadensis* extract (MIC (µg/ml) – minimum inhibitory concentration, MBC (µg/ml) – minimum bactericidal concentration).

Note: *The diagram represents the antibacterial activity of S. canadensis extract on different bacterial strains (S. aureus, E. faecalis, E. coli, K. pneumoniae, P. aeruginosa). The blue columns show MIC, expressed in µg/ml, while the orange ones – MBC, expressed in µg/ml.*

terial cultures – 150 µg /ml. The bactericidal activity varies within the concentration range 150 µg/ml – 300 µg/ml, and constitutes against *S. aureus* (209), *E. faecalis* (ATCC 19433), *P. aeruginosa* (ATCC 27853) – 150 µg/ml, and against *E. coli* (ATCC 25922) and *K. pneumoniae* (ATCC 3534/51) – 300 µg/ml (Fig. 9) [34].

Discussion

This is the first comprehensive comparative study that focused on the biology, macro- and microscopic study, phytochemistry, and main pharmacological activities of *Solidago* species from the flora of Moldova.

Similar studies have been carried out in several European countries, including Romania, Estonia, Bulgaria, Slovenia, Hungary, and Lithuania [9, 10, 12-17, 23, 38, 39]. Our results are in agreement with the majority of the evaluated studies, and we note that there is currently an increasing emphasis on the study of *S. canadensis* for its valorization for both economic and pharmaceutical purposes.

The key distinctive macroscopic features used to differentiate the plant materials of *Solidago* species were identified by examining the dried, shredded aerial parts – including stem, leaf, inflorescence, and individual flower fragments. Also, the distinct structural characteristics with diagnostic significance have been determined: the presence of secretory channels in both the rhizome and stem of both species; the stem's cross-sectional shape (polygonal in *S. virgaurea*, circular in *S. canadensis*); differences in leaf mesophyll (dorsoventral in *S. virgaurea*, equifacial in *S. canadensis*); anomocytic stomata in both species; multicellular protective trichomes of conical and flabelliform types present in both; secretory trichomes differing in structure (with a unicellular base in *S. virgaurea* and a multicellular base in *S. canadensis*); and finally, both species exhibit abundant pappus made of multiseriate bristles and spherical pollen grains [21, 22]. We note that the same mesophyll structure, and specifically multicellular conical and flabelliform trichomes, have also been mentioned by other researchers in *Solidago* species [10, 40].

In most scientific studies, the main researched group of chemical compounds in *Solidago* species are the phenolic ones. This is not by chance, but due to the fact that they are primarily responsible for the antioxidant and anti-inflammatory activities. Our results show a higher content of polyphenols, including the total polyphenols, flavonoids, and hydroxycinnamic acids in the dried extracts of *S. canadensis*, compared to that of *S. virgaurea*, which is also in agreement with other studies [10, 12, 13, 15]. One Romanian research attempts to explain the higher content of phenolic compounds in *S. canadensis* than *S. virgaurea*, based on specific ecological factors and geographical origin that could influence the accumulation of these chemical compounds [10].

Comparative phytochemical studies have demonstrated significant qualitative and quantitative differences in the flavonoid and phenolic acid profiles of these species [13-16, 41, 42]. In *S. virgaurea*, the predominant flavonoids include rutin, quercetin, isoquercitrin, and kaempferol derivatives, which are mainly localized in the aerial parts of the plant [12-13]. In contrast, *S. canadensis* is characterized by a distinct profile, with high concentrations of chlorogenic acid and rutin, along with various glycosylated flavonoids such as hyperoside and quercitrin [15]. Also, a recent Ukrainian study has demonstrated that the high flavonoid content in *S. canadensis*, especially rutin, is closely correlated with the mechanism of invasiveness, being an important element of the strategy for the development and biotransformation of a new habitat [41]. Of particular note is that, for the first time, in Lithuania, analyses of phenolic acids and flavonoids have been conducted on *Solidago × niederederi* Khek, an interspecific hybrid between *S. canadensis* and *S. virgaurea*, in order to assess its phytochemical profile and potential pharmacological relevance [42].

The presence of carotenoid pigments enhances the pharmacological potential of *Solidago* species and supports their use in antioxidant therapies, in particular being investigated as a supporting treatment in cancer [43]. Our results indicate that *S. canadensis* is richer in carotenoid pigments, but we did not identify their individual components. It should be noted that in other studies, individual carotenoid pigments have been isolated, and those characteristic for each *Solidago* species were found: *S. virgaurea* is characterized by a higher content of β-carotene and lutein in its inflorescences, whereas *S. canadensis* tends to accumulate more xanthophylls, particularly zeaxanthin, in both aerial parts and flowers [43, 44].

Saponins are another important class of biologically active compounds specific to *Solidago* species, due to the therapeutic effects they impart, in particular diuretic and antimicrobial properties [5, 7]. Also, it was revealed that triterpenoid saponins extracted from the aerial parts of *S. virgaurea* have shown inhibition of the yeast-to-hyphae transition in *Candida albicans* infection [45].

However, studies on saponins are still limited to date. The present qualitative determination of saponins demonstrated the presence of triterpene saponosides and the absence of steroid ones in the vegetal products of *Solidago* species. Our comparative quantitative saponin analysis shows that *S. canadensis* contains a higher content of saponins (500 mg SE/g DW), in contrast to *S. virgaurea* (452 mg SE/g DW) [34, 36].

Our GC-MS analysis of EO reveals a significant resemblance in the EO composition of both *Solidago* species, especially due to the prominent presence of α-pinene, which appears in greater amounts in *S. virgaurea*. Additionally, monoterpenes and sesquiterpenes were identified as the predominant hydrocarbon classes in the oils of both species, as illustrated in other studies [23, 38]. A notable distinction in our analysis lies in the limonene content – found in high concentrations in *S. canadensis,* but only in minor amounts in *S. virgaurea*. Also, pinene and limonene have been mentioned among the main constituents of *S. canadensis* EO in previous studies [38].

This study confirmed that all tested *Solidago* extracts possess strong antioxidant properties; however, *S. canadensis* extracts showed a more pronounced antioxidant action compared to those of *S. virgaurea*, as reported in other previous studies [12, 15]. Notably, leaf extracts showed significantly higher antioxidant activity in both analytical methods used. These findings are consistent with the results reported in one of the latest scientific papers from Croatia [46].

The antibacterial activity of *Solidago* species has been the subject of several studies, providing insight into their potential as sources of new natural antimicrobial agents. Our study revealed that both *Solidago* extracts showed bactericidal activity between 150–300 μg/mL, while bacteriostatic activity on several bacterial strains was more pronounced at lower concentrations for *S. virgaurea* extract (75 μg/mL). These findings are also consistent with other studies and highlight the moderate variation in antimicrobial potency between these two species [23, 47].

Both *Solidago* species have demonstrated anti-inflammatory effects in various *in vitro* and *in vivo* models, showing efficacy in reducing inflammation associated with chronic conditions such as arthritis, oxidative stress, and tissue damage [39, 47-49]. This study of the anti-inflammatory activity in 2 *in vivo* models demonstrated a mild anti-inflammatory action for both *Solidago* species. According to some authors [39, 46], the anti-inflammatory properties of *S. canadensis* extracts are attributed to both their phenolic compounds and EO. Also, in a rat model using carrageenan-induced edema, *S. virgaurea* extract demonstrated an anti-exudative effect, and both its aqueous and ethanolic extracts have been shown to reduce paw swelling and arthritic inflammation in rats [48]. Additionally, hydroalcoholic extracts of *S. virgaurea* have been found to inhibit dihydrofolate reductase, further supporting their anti-inflammatory potential [49].

Although the current study provides valuable comparative data, further investigations are required to assess the bioavailability, pharmacokinetics, and standardization of active compounds.

Conclusions

The study established clear diagnostic criteria for differentiating *Solidago virgaurea* and *Solidago canadensis* from the Moldovan flora. Comparative phytochemical and pharmacological analyses revealed that these species are rich in biologically active compounds with antioxidant, anti-inflammatory, and antibacterial properties. *S. canadensis* demonstrated a higher content of active principles and greater therapeutic potential, supporting its further investigation for pharmaceutical and nutraceutical applications.

Competing interests

None declared.

Authors' contributions

Conception and design of the work – TC and LU; acquisition of data, experimental part – CF, VI; analysis and interpretation of data – CF, VI, TC, and LU; drafting the article – CF; reviewing the article – LU, TC. All authors revised and approved the final version of the manuscript.

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Informed consent for publication

Not needed for this study.

Ethics approval

The study protocol was approved by the Research Ethics Committee of the *Nicolae Testemițanu* State University of Medicine and Pharmacy (minutes no. 36, dated 30.05.2019).

Provenance and peer review

Not commissioned, externally peer-reviewed.

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