

## Composition and bio activity of essential oils of *Solidago* spp. and their impact on radish and garden cress

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### ABSTRACT

This study aimed to identify the main components of essential oil (EO) produced by *S. canadensis* and *S. gigantea* and evaluate their phytotoxicity on radish (*Raphanus sativa* L.), and garden cress (*Lepidium sativum*). Plant samples were collected from 5-localities in east Slovakia (Šalgovík, Rúrky, Ľubotice, Solivar and V. Šebastová). The chemical compositions of EO were determined by GC-MS. Number of identified components in EO ranged from 39 to 52 for *S. canadensis* and 58 for *S. gigantea*. The major components differed between the 5- sampling sites. 1R- $\alpha$ -pinene,  $\beta$ -pinene, germacrene D, (-)-limonene, thymol, (+)*epi*-bicyclosesquiphellandrene,  $\beta$ -cadinene,  $\gamma$ -cadinene,  $\delta$ -cadinene,  $\alpha$ -muurolene,  $\gamma$ -muurolene,  $\alpha$ -cubebene,  $\beta$ -elemene were main components (over 5% each) identified in *S. Canadensis*. While curlone, tumerone and  $\delta$ -cadinene were identified as dominant components in *S. gigantea*. Two samples from Rúrky and Ľubotice were stimulatory and one sample from Solivar was inhibitory to seed germination of radish. Samples from Rúrky and V. Šebastová significantly inhibited the seed germination of garden cress. Application of EO from Rúrky and V. Šebastová on radish and EO from Ľubotice and V. Šebastová on garden cress significantly stimulated the radicle elongation. However, the EO from Solivar inhibited the radical elongation of garden cress.

**Key Words:** Allochemicals, allelopathy, garden cress, invasive species, *Lepidium sativum*, natural components, phytotoxicity, radish, *Raphanus sativus*, *S. canadensis* L., *Solidago gigantea* Aiton.

### INTRODUCTION

The genus *Solidago* [family Asteraceae (tribe Astereae)] is indigenous to North America and includes about 100 species of North American wild plants and more than dozen species in South America, Europe and Asia. All species are herbaceous and most of them are difficult to distinguish from one another (3). The specie *Solidago virgaurea* L., is native to Europe (24,58). *Solidago gigantea* Aiton is a geophytic rhizomatous perennial plant, up to 2 m high. Due to clonal growth, the species forms dense monocultures (34). This species is native to North America and was introduced to Europe in the 19<sup>th</sup> century as an ornamental species. *Solidago canadensis* L. is perennial rhizomatous plant native to North America and was initially introduced as ornamental plant in China in 1930s. Then, it escaped into the wild and formed large clonal colonies, becoming a major weed in China

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(32,54). In Europe, *Solidago* species don't suffer from herbivory and show increased vigour and competitive ability than native populations (34). Both these species suppress the original indigenous plants (3) and are now most aggressive plant invaders in Europe (60,61).

Biological invasions are receiving more attention due to their increasing ecological and economic impacts, yet the mechanisms of successful plant invasions are not well known. Most introduced plants have strong plastic responses to various environmental variables (light, nutrients or competition) (33). Many studies of invader plants have examined the biological (5,45), ecological characteristics dynamics (50), distributions (10), resource supply rates (19) or impact on native species (33). Mechanisms involving the interactions with competitors appear the key to understand the for exotic invasions (14,42). Invaders possess allelopathic, defensive, or antimicrobial chemicals, to which native organisms are not adapted (13).

Previous studies have focused on examining the components (mono and sesquiterpenes) of essential oil (EO) of *Solidago* spp. (3,27,36,37,43). Generally, terpenes in medicinal, aromatic or spicy plants are antibacterial, antiviral, antioxidative, inhibitory also phytotoxic or allelopathic (1,7,12,18,49,51,53,56). Plants release allelochemicals into the environment through volatilization from leaf tissues or root exudates (9,25,57). The effects of volatile components produced by plants in plant-plant interactions have been investigated. Many invasive plants (*Pinus ponderosa*, aromatic *Origanum onites* L. or *Rosmarinus officinalis* L.) influences the seedlings growth of other invasive plants such as *Bromus tectorum* or weeds (*Avena Sterilis*, *Sinapis arvensis*) through allelopathic interference (8,18,53).

The invasiveness in Asteraceae family, depends on allelopathic interactions, hence, the understanding of the mechanisms of successful invasion of highly noxious plant invaders to succeed is important for ecosystem management (45). Present literatures describes the possible phytotoxic effects of aqueous or methanolic extract from *Solidago* spp. (40,43,64), but the bioactivity of EO extracted from test species has not been studied.

This study aimed to identify the chemical composition of EO extracted from two *Solidago* species and evaluate their potential phytotoxic effects on radish (*Raphanus sativa* L.) and garden cress (*Lepidium sativum*). This new approach would help us to understand, if chemical effects are necessary for the successful invasions of these *Solidago* spp.

## MATERIAL AND METHODS

### Plant material

Six randomly selected plant samples were collected in July-August 2013 at full-bloom stage from 5 sites in the invaded grasslands in urban and suburban zones of Prešov, viz., Šalgovík (48°59'50"N 21°18'19"E), Rúrky (49°00'8"N 21°12'21"E), Ľubotice (49°0'13"N, 21°16'21"E), Solivar (48°58'2.06"N 21°17'8.24"E) were *S. Canadensis* and from V. Šebastová (49°0'29"N 21°20'8"E) was *S. gigantea*. Species were determined according to Cvachová and Gojdičová (15) and the National Register of Soil reported that these sites are presently grasslands without harvesting or grazing and were dominated (>80%) by invasive *S. canadensis* and *S. gigantea*. The fresh plant material

were dried at room temperature in thin layer on filter paper sheets. The drying was done for one week until the material reached constant dry weight.

**Methanolic extracts:** Five g of each sample was placed in a glass flask and poured with 100 mL of methanol (Sigma Aldrich, Germany). After one week, the extracts were used for the TLC (Thin-layer chromatography) analysis.

**Isolation of essential oil:** Twenty g of each sample of *Solidago* spp. were grounded in a blender and then hydrodistilled in a Clevenger-type apparatus for 2 h. The oils were solubilized in *n*-hexane and stored under N<sub>2</sub> at +4 °C in dark until analysis. The plant materials yielded colourless-yellow oils. Pure EO for analysis by gas chromatography–mass spectrometry (GC-MS) were diluted to 1:1000 ratio in *n*-hexane.

#### GC-MS analyses and identification of components

GC-MS analyses were carried out on a Varian 450-GC connected with a Varian 220-MS. Separation was achieved using a FactorFour™ capillary column VF 5ms (30 m × 0.25mm i.d., 0.25 µm film thickness). Injector type 1177 was heated to a temperature of 220 °C. Injection mode was splitless (1 µL of a 1:1000 *n*-hexane solution). Helium was used as a carrier gas at a constant column flow rate of 1.2 mL min<sup>-1</sup>. Column temperature was programmed: initial temperature was 50 °C for 10 min, then increased to 100 °C at 3 °C min<sup>-1</sup>, maintained isothermal for 5 min and then increased to 150 °C at 10 °C min<sup>-1</sup>. The total time for analysis was 87.67 min. Analysis was also run, with the same operating conditions, by using an apolar DB-5 fused silica capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). In both cases, helium was used as carrier gas (1.2 mL min<sup>-1</sup>). The mass spectrometer trap was heated to 200 °C, manifold 50 °C and transfer line 270 °C. Mass spectra were scanned every 1 s in the range 40–650 *m/z*.

Most constituents were identified by gas chromatography by comparison of their Kovats retention indices (Ri) with either those of the literature (25, 35) or with those of authentic compounds available in our laboratories. The Kovats retention indices were determined in relation to the *t<sub>R</sub>* values of an homologous series of *n*-alkanes (C<sub>10</sub>–C<sub>35</sub>) on both capillary columns, under the same operating conditions. Further identification was made by comparison of the mass spectra on both columns with either those stored in NIST 02 and Wiley 275 libraries or with those from the literature (2,16). Components relative concentrations were obtained by peak area normalization. No response factors were calculated.

#### Bioassay

The experimental treatments consisted of two factors: (i). Test plants : 2 [radish (*Raphanus sativus* L.), garden cress (*Lepidium sativum* L.)] and (ii). Essential oil concentration : 6 (2.5, 1.25, 0.625, 0.25, 0.125, and 0.062 µg mL<sup>-1</sup>). The essential oils were dissolved in distilled water/acetone 99.5:0.5 and diluted to prepare the desired concentrations (2.5, 1.25, 0.625, 0.25, 0.125, and 0.062 µg mL<sup>-1</sup>). Distilled water/acetone 99.5 : 0.5 was used as control than control in distilled water.

Test seeds were surface sterilized in 95% EtOH for 15 s and rinsed thrice in distilled water. Ten sterilised seeds were sown into each Petri dish (90 mm dia) containing 5- layers of Whatman filter paper. In each petri plate 7 mL of essential oil concentration solutions or distilled water was added as per treatments. Each treatment was repeated thrice in design

previously described (17). The petri plates were kept in growth chamber ( $20\pm 1$  °C, natural photoperiod, Sanyo, MLR-351H). The seed germination was recorded every 24 h. A seed was considered germinated, when the root protrudes 1 cm from the seed coat (18). The radicle length (cm) was measured after 120 h.

**Statistical Analysis:** Data were expressed as % stimulation of inhibition effect for both germination and radicle elongation. Data were ordered in homogeneous sets, and the Fishers` s LSD test was applied (11).

## RESULTS AND DISCUSSION

**Chemical fingerprint:** It's difficult to differentiate between the *S. canadensis* and *S. gigantea* from the morphological characters, because the description in morphological botanical key (15) is almost the same, even if in Italian Flora a distinction based on hair presence is proposed (48). Our identification was confirmed by TLC analysis (Figure 1). Affiliation to the same species within the genus was tested by simple visual test to compare their methanolic extract fingerprints. Results showed that the sample V. Šebastová had different fingerprint than other four samples from 4 different localities (Šalgovík, Růrky, Lúbotice and Solivar) which belong to *S. canadensis* and the sample V. Šebastová was identified as *S. gigantea*.

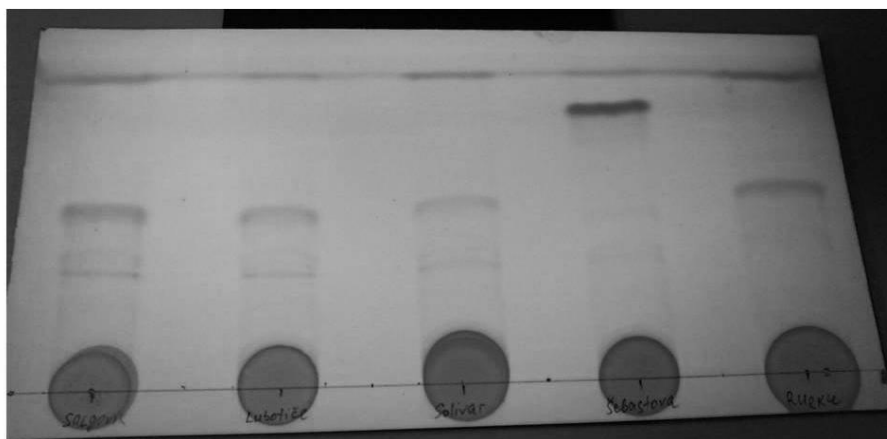


Figure 1. TLC analysis, samples from localities Šalgovík, Lúbotice, Solivar and Růrky have the same biochemical fingerprint and belong to the species *S. canadensis*. V. Šebastová have different fingerprint and belongs to species *S. gigantea*.

**EO yield:** Fresh aerial parts were dried and then hydrodistilled. The extracted EO were colourless or with light yellow colour with strong herbaceous, aggressive odour. The EO yields from sample Šalgovík, Růrky, Lúbotice, Solivar and V. Šebastová were 0.5, 1.2, 0.8, 0.7, and 0.6%, respectively.

**EO composition:** The most abundant chemical components identified in EO extracted from five samples (Šalgovík, Růrky, Lubotice, Solivar and V. Šebastová) are presented in Table 1. Components are listed according to their retention times on a VF-5 and DB-5 capillary column. Altogether, 70 components were identified, 39 in the EO from the *S. canadensis* sample Šalgovík, 50 in the EO from sample Růrky, 52 in the EO from sample Lubotice, 51 in EO from sample Solivar and 58 components in EO of *S. gigantea* in sample V. Šebastová, accounting for 96.6, 90.6, 96.5, 95.4 and 95.6% of the total oil, respectively.

In *S. canadensis* oils, the highest amount was of sesquiterpene hydrocarbons [73.0, 76.1, 63.1% in samples Růrky, Lubotice and Solivar]. The most abundant components of this fraction were  $\beta$ -elemene (2.9-12.5%), germacrene D (11.1%), (+)-epi-bicyclosesquiphellandrene (4.3-9.8%),  $\beta$ -cadinene (6.0-9.0%),  $\gamma$ -muurolene (3.0-7.9%),  $\delta$ -cadinene (0.8-7.4%),  $\alpha$ -muurolene (4.7-6.9%),  $\gamma$ -cadinene (4.7-5.2%) and  $\alpha$ -cubebene (0.1-5.0%). The other sesquiterpene hydrocarbons were either present in low amounts and traces or absent. limonene (4.3-9.0%), 1R- $\alpha$ -pinene (1.8-8.1%) and (-)- $\beta$ -pinene (3.0-6.5%) were the main components in the monoterpene hydrocarbons in oils from samples Růrky, Lubotice and Solivar, respectively.

The chemical composition of EO of invasive goldenrod populations varied with collections sites in the same specie (*S. canadensis*) as well as between the two species (*S. canadensis* and *S. gigantea*). The EO of *S. canadensis* from sample Šalgovík was quite different, because it contained same amount of monoterpene hydrocarbons (46.4%) and sesquiterpene hydrocarbons (41.2%), the main components were 1R- $\alpha$ -pinene (36.3%), (-)-limonene (7.8%) and germacrene D (9.9%). There was also an appreciable content of phenolic compound (7.3% thymol) in the oil from sample (Šalgovík) and there were no oxygenated sesquiterpenes. *S. gigantea* oil contains sesquiterpenes hydrocarbons (47.4%), represented by  $\delta$ -cadinene (5.4%),  $\gamma$ -muurolene (4.8%),  $\alpha$ -cubebene (4.5%),  $\gamma$ -cadinene (4.4%), (+)-epi-bicyclosesquiphellandrene (4.3%),  $\alpha$ -muurolene (3.8%) and  $\beta$ -elemene (3.1%) as main compounds. Oxygenated sesquiterpenes (29.3%) were represented by curlone (14.4%) and tumerone (14.0%) as the most abundant components.

Biochemical studies indicated that the genus *Solidago* exhibits different terpenoid profile (23,63). The main components of two samples of *S. gigantea* collected in central Poland were  $\alpha$ -pinene (4.1 and 7%), myrcene (2.5 and 2.6 %), *p*-cymene (0.6 and 2.2 %), (-)-bornyl acetate (2.9 and 4.4 %),  $\alpha$ -gurjunene (4.0 and 6.1%),  $\gamma$ -gurjunene (2.1 and 2.5%), (-)-germacrene D (21.6 and 23.5 %), (-)-ledol (1.2 and 2.1%), eudesma- 4(15),7-dien-1-ol (1.9 and 2.5 %) and (-)-cyclocolorenone (8.1 and 32.4 %) (36). In another research, the essential oil of *S. gigantea* was dominated by sesquiterpenes:  $\alpha$ -gurjunene (16.6%), germacrene D (12.8%), (-)-cyclocolorenone (32.8%) and ledol (4.9%) (37).

The available literature also reports higher variability in chemical composition of EO of *S. canadensis*. In some publications germacrene D (15.2-69.7%), bornyl acetate (1.8-9.2%) and limonene (0.2-12.0%) are three major components (22,27,38,39,41,44). The dominant component in *S. canadensis* was  $\alpha$ -pinene (14.7-59.5 %) (37,50,62). Contrarily in the *S. canadensis* essential oil no germacrene D was found (26,31). Considering the remarkable variations in the EO of two *Solidago* species from different localities, it is possible to hypothesize the presence of different chemotypes and consequently, more studies are needed to clarify the relationship between the chemical composition of EO and biotypes.

Table 1. The most abundant components in essential oil isolated from the aerial parts of *Solidago* spp. collected in Šalgovík, Rúrky, Lúbotice, Solivar and V. Šebastová.

Rt	Compound name and class	<i>RI<sub>a</sub></i> <sup>a)</sup>	<i>RI<sub>b</sub></i> <sup>a)</sup>	Content (%) in various Sampling sites					Identif. b)
				Šalgovík	Rúrky	Lúbotice	Solivar	V.Šebastová	
9.561	1R- $\alpha$ -pinene	1011	939	36.3	1.8	4.4	8.1	2.7	1,2,3
12.702	(-)- $\beta$ -pinene	1101	980	0.5	4.6	3.0	6.5	1.9	1,2,3
16.273	(-)-limonene	1177	1024	7.8	5.3	4.3	9.0	4.3	1,2,3
32.450	thymol	1388	1289	7.3	-	2.6	1.7	-	1,2,3
35.541	$\beta$ -elemene	1592	1389	4.2	4.5	12.5	2.9	3.1	1,2
36.506	$\gamma$ -muurolene	1619	1478	2.9	7.9	3.0	5.7	4.8	1,2
36.857	(+)- <i>epi</i> -bicyclosesquiphellandrene	1628	1521	2.6	9.8	4.3	5.1	4.3	1,2
37.494	$\beta$ -cadinene	1645		0.8	9.0	8.4	6.0	0.5	1,2
37.705	germacrene D	1650	1484	9.9	-	11.1	-	-	1,2,3
38.022	$\alpha$ -cubebene	1659	1345	3.5	5.0	2.8	0.1	4.5	1,2
38.565	$\gamma$ -cadinene	1673	1513	3.0	-	5.2	4.7	4.4	1,2
38.727	$\delta$ -cadinene	1677	1522	3.1	7.4	0.8	1.1	5.4	1,2
39.257	$\alpha$ -muurolene	1690	1500	2.8	6.9	4.7	5.0	3.8	1,2
44.304	tumerone	1810	1668	-	-	-	-	14.0	1,2
46.045	curlone	1848		-	-	-	-	14.4	1,2
	<b>Total identified</b>			<b>96.6</b>	<b>90.6</b>	<b>96.5</b>	<b>95.4</b>	<b>95.6</b>	
	Monoterpene			46.4	13.0	12.9	25.8	9.5	
	Hydrocarbons								
	Oxygenated Monoterpenes			1.7	3.1	0.3	3.4	7.9	
	Sesquiterpene			41.2	73.0	76.1	63.1	47.4	
	Hydrocarbons								
	Oxygenated Sesquiterpenes			t	1.5	4.5	1.3	29.3	
	Phenolic compounds			7.3	-	2.7	1.8	1.5	

<sup>a)</sup>*RI<sub>a</sub>* and *RI<sub>b</sub>*: Kovats retention indices determined relative to the  $t_R$  of a series of *n*-alkanes (C<sub>10</sub>-C<sub>35</sub>) on VF-5 and DB-5 columns, respectively; <sup>b)</sup> Identification method: 1, comparison of Kovats retention indices with published data; 2, comparison of mass spectra with those listed in the NIST 02 and Wiley 275 libraries and with published data; 3, coinjection with authentic compound. <sup>c)</sup> -: Not detected. <sup>d)</sup>.

**Phytotoxic activity of the EO:** The EO extracted from 5 samples affected significantly the seed germination of test plants in two ways. The application of EO from the sample Rúrky at 2.500  $\mu\text{g mL}^{-1}$  and 0.062  $\mu\text{g mL}^{-1}$  doses and from the sample Lúbotice at the 0.250  $\mu\text{g mL}^{-1}$  dose stimulated the seed germination of *R. sativus* L. over the control by

75.0%, 83.3% and 69.3%, respectively (Table 2). However, the application of EO from the sample Solivar at 0.062  $\mu\text{g mL}^{-1}$  dose, caused 66.7 % inhibition in *R. sativus* L. seed germination than control. Seed germination of *L. sativum* L. was inhibited significantly after application of EO from the sample Růrky at 0.625  $\mu\text{g mL}^{-1}$  doses (17.8 % inhibition in control) and from the sample V. Šebastová at 0.025  $\mu\text{g mL}^{-1}$  dose, which was 29.1 % under control. The EO from sample Šalgovík did not affect the seed germination of both test species.

Table 2. Effects of doses of essential oil (EO) isolated from the aerial parts of *Solidago* spp. collected from 5- sites on the seed germination of radish and garden cress at 120 h after Sowing.

Test species	EO Doses [ $\mu\text{g mL}^{-1}$ ]	<i>Solidago</i> sp. Sampling sites				
		Šalgovík	Růrky	Lubotice	Solivar	V. Šebastová
<i>Raphanus sativus</i>	0.000 (control)	2.67	4.00	4.33	7.00	7.00
	0.062	3.67	7.33*	5.33	2.33**	7.33
	0.125	2.00	6.00	6.00	5.67	7.33
	0.250	5.33	6.00	7.33*	6.00	6.33
	0.625	4.00	6.33	3.67	4.67	7.33
	1.25	3.00	4.67	4.33	7.67	7.00
	2.500	1.67	7.00*	5.00	5.00	8.67
<i>Lepidium sativum</i>	0.000 (control)	9.67	9.33	9.67	9.67	8.00
	0.062	10.0	9.00	8.67	9.67	8.33
	0.125	9.00	8.33	9.67	9.67	8.33
	0.250	9.67	9.00	9.33	8.67	5.67**
	0.625	9.00	7.67*	9.00	9.33	8.00
	1.250	9.67	10.0	9.33	9.67	7.33
	2.500	9.67	8.00	9.33	9.33	7.00

**Radical elongation:** EO extracted from three samples [Růrky, Lubotice and V. Šebastová] stimulated the radical elongation of *R. sativus* L. and *L. sativum* L. over the control (Table 3). Růrky sample at 3-doses (0.625, 0.250 and 0.062  $\mu\text{g mL}^{-1}$ ) significantly stimulated the elongation of *R. sativum* L. roots, which was 302.7 %, 267.6% and 405.4 % over the control. EO sample Lubotice at 2.500 and 0.625  $\mu\text{g mL}^{-1}$  dose significantly stimulated the root of *L. sativum* L. (34.2 % and 26.1 % over control) and sample V. Šebastová at 0.250 and 0.062  $\mu\text{g mL}^{-1}$  doses significantly stimulated the root of *R. sativus* L. (53.6 % and 125.8 % over control) and at dose 0.062  $\mu\text{g mL}^{-1}$  doses significantly stimulated the root of *L. sativum* L. Only EO sample Solivar at 4-doses (0.625, 0.250, 0.125 and 0.062  $\mu\text{g mL}^{-1}$ ) significantly inhibited the root elongation of *L. sativum* L. (30.1 %, 35.9 %, 23.4 % and 28.9%, respectively, over control). However, the EO from sample Šalgovík, had no effect on the seed germination and root elongation of both test (Figure 2 and 3).

The stimulatory/inhibitory influence of essential oils on radical elongation may be explained with hormesis phenomenon. As per literature, some doses of same oil can be inhibitory or stimulatory. The concept of “low dose stimulation - high-dose inhibition” or “hormesis” is supported by field observations (55). The exposure to novel environments or

toxic substance increases the variability in phenotypic traits (enzyme activity, morphological features and growth), however, the reasons for such increases and their adaptive implications remain unclear (49).

Table 3. Effects of different doses of the essential oil (EO) isolated from the aerial parts of *Solidago* spp. collected from 5- sites on the root elongation (cms) of radish and garden cress at 120 h after Sowing.

Test species	EO Doses [ $\mu\text{g mL}^{-1}$ ]	<i>Solidago</i> sp. Sampling sites				
		Šalgovík	Rúrky	Lubotice	Solivar	V.Šebastová
		Root length (cm)				
<i>Raphanus sativus</i>	0.000 (control)	1.13	0.37	0.47	1.84	1.51
	0.062	1.67	1.87*	0.59	0.88	3.41**
	0.125	1.00	1.19	1.18	1.80	2.31
	0.250	2.67	1.36*	1.72	1.69	2.32*
	0.625	1.46	1.49*	0.78	1.52	1.78
	1.25	0.97	0.57	1.70	2.88	1.91
	2.500	0.65	0.61	0.82	1.84	2.34
<i>Lepidium sativum</i>	0.000 (control)	6.81	7.90	4.82	7.61	2.73
	0.062	7.16	7.34	3.53	5.41*	4.73*
	0.125	6.03	6.79	4.75	5.83*	4.30
	0.250	6.46	8.10	3.87	4.88*	2.87
	0.625	6.48	5.84	6.08*	5.32*	3.60
	1.250	6.43	8.50	6.90	6.35	2.63
	2.500	7.97	6.42	6.47*	5.88	2.32

Significant differences compared to control:  $p < 0.05$  (\*),  $p < 0.01$  (\*\*),  $p < 0.001$  (\*\*\*)

Zhou and Guo (64) tested the allelopathic effects of water extracts from *S. canadensis* roots and rhizospheric soil on the seed germination, root extension and elongation of seedlings of Chinese cabbage (*Brassica rapa* L.) and radish (*Raphanus sativus* L.). Results showed that water extracts from roots and rhizospheric soil generally inhibited selectively the seed germination. Water extracts from roots stimulated radicle extension of radish seedlings at  $0.05\text{g.mL}^{-1}$ , but had no effect on both species at tested doses. The influence of different doses of extracts of *S. canadensis* root and rhizome was tested on 11 native plants. The inhibitory effects of the extracts from both *S. canadensis* root and rhizome were enhanced with increase in dose and rhizome extract had higher effect. Root extract had little effect on the seed germination but rhizome extract inhibited the germination of all test plants, though the inhibitory effects varied with different species (43).

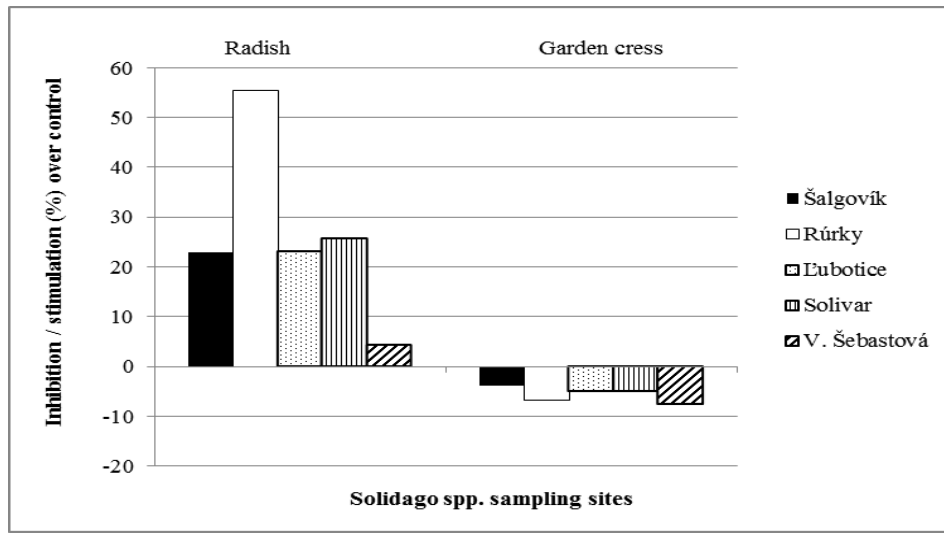


Figure 2. Inhibitory / stimulatory effects of *Solidago* spp. essential oil sampled from five sites on seed germination of radish and garden cress.

Li *et al.* (40) tested the allelopathic interactions between two species (*S. canadensis* and *Phragmites australis*). Researchers analyzed the differences in the seed germination rate and sprout length after treatment with different doses of goldenrod extracts. Low doses ( $12.5$  and  $25$  mg mL<sup>-1</sup>) slightly promoted the seed germination rates, while high doses ( $50$ ,  $100$ , and  $200$  mg mL<sup>-1</sup>) were very inhibitory.

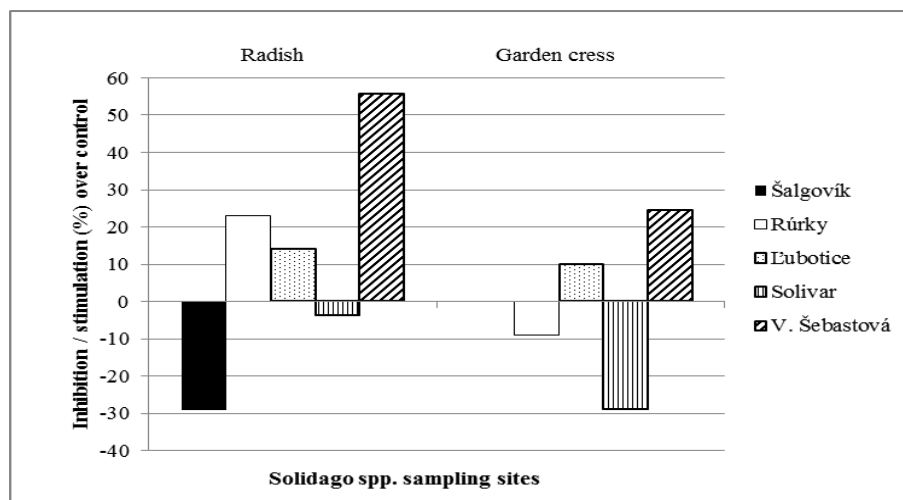


Figure 3. Inhibitory / stimulatory effects of *Solidago* spp. essential oil sampled from five sites on root elongation of radish and garden cress.

Dudai *et al.* (20) reported that monoterpenes act on seeds at very low levels, and their contents in various parts of wheat seeds differed. Many species release phytotoxic monoterpenes ( $\beta$ -pinene, and limonene) that hinders the development of herbaceous species (4,47). The germacrene D is also allelopathic (21,50). Recently, Areco *et al.* (6) reported that  $\beta$ -pinene reduced the speed of germination and seedling growth of maize.

Some papers also reported the possible action mechanism of such activity. Ibrahim *et al.* (30) reported the effects of limonene on the growth and primary physiology of cabbage (*Brassica oleracea* L) and carrot (*Daucus carota* L) plants. Nishida *et al.* (46) demonstrated that monoterpenes [Eucalyptol,  $\alpha$ -pinene, camphor and camphene] inhibited the mitosis through interference with DNA synthesis in meristematic cells. Chowhan *et al.* (28,29) reported that monoterpenes [ $\alpha$ -pinene, camphor, camphene (46) and citronellal (52)] inhibited the cell division in growing root tips and  $\beta$ -pinene inhibited the germination and early growth due to membrane peroxidation. Barney *et al.* (9), reported that as in our case, none of the individual monoterpenes caused observed phytotoxicity, but it was a synergistic effect of many monoterpenes. The presence of bioactive terpenoids suggested their potential role in plant establishment and proliferation in introduced habitats.

## CONCLUSIONS

Five populations of invasive goldenrod species (*S. gigantea* and *S. canadensis*) were investigated in east Slovakia. Composition of essential oils of these spp. differed among localities. The samples of *S. canadensis* and *S. gigantea* significantly stimulated the radical elongation of radish and garden cress test plants. However, more detailed studies are needed on the chemical compositions and biological activity of these species. Our investigation showed the impact of volatiles on their invasiveness but the mechanism is not clear.

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