Autoallelopathic potential of aqueous extracts from Canadian goldenrod (*Solidago canadensis* L.) and giant goldenrod (*S. gigantea* Aiton)

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Abstract

Production of allelopathic substances is a factor determining the ecological success of invasive plants—Canadian goldenrod (*S. canadensis* L.) and giant goldenrod (*S. gigantea* Aiton). This research aimed at evaluating the autoallelopathic effect of aqueous extracts (AEs) prepared from various parts of Canadian goldenrod and giant goldenrod against vegetative growth, and biomass accumulation of both goldenrods. In the stage of 5–6 leaves, goldenrod plants, were foliar sprayed with AEs, at concentrations of 5 or 10%. The biochemical properties of AEs, i.e., total phenolic content, total antioxidant potential and selected plant hormones, were examined. Two and ten days after spraying (DAS), damages to aboveground parts of goldenrods (necrosis and wilting) were visually assessed. The fresh mass of above- and belowground parts of goldenrods were measured 21 DAS. AEs from various parts of Canadian goldenrod or giant goldenrod displayed autoallelopathic properties of inhibitory nature. The phytotoxic potential of AEs varied depending on their source. Canadian goldenrod was more susceptible to the AEs, manifested by more significant damages to aboveground parts and a greater decrease in above- and belowground biomass. The most effective against growth and development of Canadian goldenrod and giant goldenrod were AEs from rhizomes, which caused a reduction of fresh biomass of goldenrods up to 42%, compared to water-treated control.

Keywords Autotoxicity · Phenolic compounds · Antioxidant potential · Phytohormones

Introduction

Canadian goldenrod (*S. canadensis* L.) and giant goldenrod (*Solidago gigantea* Aiton) are native to North America. However, they widely spread in many regions of Europe, Asia, and Australia, where they are considered as invasive plants (Shen et al. 2005; Dong et al. 2006; Huang et al. 2012;

Szymura and Szymura 2015; Bochenek et al. 2016; Weber 2017; Follak et al. 2018). Goldenrods pose a serious threat to native species, competing with them for ecological niches and displacing them from their habitats (Dong et al. 2006). According to many authors, the production of allelopathic substances, which inhibit the growth and development of other plants, is one of the factors determining the ecological success of Canadian goldenrod and giant goldenrod (Abhilasha et al. 2008; Shen et al. 2008; Yuan et al. 2013; Baličević et al. 2015). In a dense stand of goldenrods, a phenomenon of autoallelopathy (autotoxicity) may also occur, which indicates a negative or positive interaction of plants of the same species on each other (Thiébaud et al. 2019). It has important ecological implications, minimizing intraspecific competition, extending seed dispersal and regulating plant population over time and space (Singh et al. 1999; Liu et al. 2008). Autotoxicity has been identified in many field crops (Yu et al. 2000; Ben-Hammouda et al. 2002; Chon and Kim 2002; Wu et al. 2007) and weeds (Sołtys et al. 2010).

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However, the available scientific literature lacks information on the autotoxicity of invasive goldenrods.

Allelopathy is often referred to as a “chemical competition” and is correlated with so-called specialized metabolites, among which phenolic compounds are of special importance. They are composed of phenolic acids, flavonoids, and tannins, important for plant protective functions, i.e., insecticidal and antifeeding (Balasundram et al. 2006) as well as antioxidant function (Kähkönen et al. 1999; Balasundram et al. 2006). Another important group of plants specialized metabolites are phytohormones such as abscisic acid (ABA), which regulates seed dormancy, germination, cell division and elongation, floral induction, and responses to environmental stresses such as cold, drought, or pathogen attack (Finkelstein 2013; Hauser et al. 2017). The other compounds, i.e., jasmonic acid (JA) and salicylic acid (SA) play important roles in plant defense systems against necrotrophic, biotrophic and hemibiotrophic pathogens (Hayat et al. 2007; Tamaoki et al. 2013).

This research aimed at assessment of (i) total phenolic content, selected phytohormones content, and antioxidative potential of aqueous extracts (AEs) prepared from different parts of Canadian goldenrod and giant goldenrod; (ii) autoallelopathic potential of the foliar sprayed AEs and (iii) correlation between content of the examined chemical compounds of AEs and their allelopathic effect.

The research hypothesis assumed that (i) Canadian goldenrod and giant goldenrod release allelopathic substances which influence the initial growth and development of each of them; (ii) total phenolic content, antioxidative potential and selected phytohormones content in AEs from Canadian goldenrod and giant goldenrod depend on plant parts from which the extracts are obtained.

Materials and methods

Plant materials

The plants of Canadian goldenrod and giant goldenrod for extracts preparation were collected from two stands located in southern Poland (Skalbmierz community, Świętokrzyskie voivodeship). The aboveground parts of goldenrods in the vegetative phase (shoot development stage) as well as in the generative phase (flowering stage) were harvested at the beginning of June and in mid-August 2013, respectively. Goldenrod rhizomes with adventitious roots were dug out from the soil arable layer at the end of vegetation season—in mid-October 2013 (when the process of generating new rhizomes nears the end). Immediately after being dug out, rhizomes were cleaned and rinsed of residual soil.

The collected plant material was air-dried, packed into paper bags and stored at room temperature in a shaded, dry and well-ventilated place until the commencement of the experiment.

Seeds of Canadian goldenrod and giant goldenrod were collected from ten stands located in southern Poland (Kraków, Kocmyrzów-Luborzyca, Proszowice and Skalbmierz community; Małopolskie and Świętokrzyskie voivodeship) at the beginning of October 2013. The seeds were used to create two separate pooled samples for each goldenrod species. Then seeds of *S. canadensis* and *S. gigantea* were randomly selected from each sample and transferred onto Petri dishes to germinate. After three days, germinated seeds were transferred into plastic seedling trays which were filled with a mixture of universal garden soil (Biovita, Tenczynek, Poland) with sand at a 3:1 ratio.

Preparation of extracts

AEs were prepared according to Baličević et al. (2015) and Synowiec and Nowicka-Poteć (2016). The air-dry plant material was powder grounded in an industrial mill SM 100 C (Retsch Verder, Katowice, Poland). Then the powder material, with mass adjusted to appropriate concentration (w/v), was mixed intensively with distilled water and put aside for 24 h (in a shaded place at room temperature). After this time, the extracts were filtered few times through double-layer of filter paper to remove debris.

Prepared extracts:

- From Canadian goldenrod in the vegetative phase, in the generative phase and from its rhizomes, at concentrations of 5% and 10%;
- From giant goldenrod in the vegetative phase, in the generative phase and from its rhizomes, at concentrations of 5% and 10%.

Biochemical analysis of extracts

After filtrating, 20 mL of each AE was taken for biochemical analyses. The analyses were carried out in the laboratory of the Franciszek Górski Institute of Plant Physiology in Kraków.

Folin–Ciocalteu (F–C) assay for total phenolic content

The assay for total phenolic content (TPC) was performed according to Singleton et al. (1999) with modifications by Bach et al. (2015). Twenty-five μL of AE were diluted to 500 μL with deionized water and 200 μL Folin–Ciocalteu

reagent (POCH, Gliwice, Poland) was added. After 10 min incubation, 700 μL saturated Na_2CO_3 was added. Samples were mixed and, after 2 h incubation (25 °C) in darkness, centrifuged, transferred to 96-well plates, and the absorbance at 760 nm was read (Synergy II, Biotek, USA). The results were expressed as gallic acid equivalent.

CUPRAC assay for total antioxidant potential

The CUPRAC (CUPric Reducing Antioxidant Capacity) method (Ozyürek et al. 2007) adopted by Biesaga-Kościelniak et al. (2014) was applied. Fifty μL of AE was transferred to 96-well plates previously filled with the 50 μL of 10 mM Cu^{2+} 7.5 mM neocuprine and pH 7.0 1 M ammonia-acetate buffer. The plates were shaken for 15 min at 25 °C. Then absorbance was read at 450 nm (Synergy II). The content of antioxidants was expressed as the Trolox equivalent.

Stress-related phytohormones and benzoic acid analysis

Selected stress-related phytohormones: abscisic (ABA), salicylic (SA), jasmonic (JA) and SA precursor benzoic (BeA) acids were assessed according to the procedure described by Hura et al. (2017). Ultrahigh-performance liquid chromatography-electrospray ionization tandem mass spectrometry (UHPLC–ESI–MS/MS) was used. Freeze-dried samples equal to 10 mL of AE were extracted in 3 cm^3 methanol/water/formic acid, ($\text{MeOH}/\text{H}_2\text{O}/\text{HCOOH}$, 15/4/1 v/v/v) after the addition of stable isotope-labeled internal standard solution (ISTD). ISTD consisted of [2H6]cis,trans-abscisic acid, [2H5]benzoic acid, [2H4]salicylic acid and [2H5]jasmonic acid. Evaporated pooled supernatant was resuspended and cleaned up on mixed-mode SPE cartridges (Bond Elut Plexa PCX, Agilent, Santa Clara, CA, USA). An Agilent Infinity 1260 UHPLC system coupled with 6410 Triple Quad LC/MS with an electrospray interface (ESI) (Agilent Technologies, USA) was used. The separation was achieved on an Ascentis Express RP-Amide analytical column (2.7 μm , 2.1 mm $\times$ 150 mm; Supelco, Bellefonte, PA, USA) at a linear gradient of H_2O vs. acetonitrile with 0.01% of HCOOH. Quantification was carried out based on the MRM method with the linear range of a standard curve constructed with known amounts of phytohormones taking ISTD recovery into account. Further technical details are given by Dziurka et al. (2016) and Płazek et al. (2018). All standards except JA-D, which was supplied by CND Isotopes (Quebeck, Canada), were supplied by OIChemIm (Olomouc, Czech Republic), whereas other chemicals were purchased from Sigma-Aldrich (Poznań, Poland).

Plant spraying and measurements

AEs were foliar applied on goldenrods immediately after filtration. Each AE was sprayed on 5 plants (replications) of each goldenrod species. Spraying was done using sterilized 100 mL syringes (Polfa Lublin, Poland) equipped with a small-drop sprayer Turbo TeeJet (Dąbrowa, Poland), recommended for contact and systemic herbicides. The plants were sprayed up to the drip point (8.5 cm^3 AE per 100 cm^2).

After spraying, visual assessment of damages (in percents) to the aboveground parts of both *Solidago* species was carried out twice: (i) 2 days after spraying (DAS), when the first damage appeared and (ii) 10 DAS. The damage included wilting (loss of rigidity of non-woody plant parts) and necrosis (premature death of plant cells in living tissue caused by cell injury).

Three weeks after spraying, goldenrods were cut down and biomass of above- and belowground parts of a single plant per each treatment was weighed with accuracy 0.01 g.

Statistical analysis

The normality of the distributions of the observed traits was tested using Shapiro–Wilk’s test (Shapiro and Wilk 1965). A two-way fixed analysis of variance (ANOVA) was carried out to determine the effects of AE, concentration and concentration $\times$ AE interaction on the variability of observed traits, independently for *S. canadensis* and *S. gigantea*. Mean values and standard deviations were calculated. Moreover, Fisher’s least significant differences (LSDs) were also estimated at the significance level $\alpha = 0.05$.

The relationships between observed traits were assessed based on Pearson’s correlation coefficients using FCORRELATION procedure in GenStat 18th edition, independently for *S. canadensis* and *S. gigantea*.

Results

Total phenolic content (TPC) and total antioxidant potential (TAP) in extracts

AEs differed in TPC, depending on goldenrods species, plant part and extract concentration (Table 1). A significantly higher TPC was recorded in AE from *S. canadensis* in the vegetative phase at a concentration of 10% (1.187 mg mL^{-1}), in comparison to the other AEs from this species. In turn, in the case of *S. gigantea*, a significantly higher TPC displayed AEs from plants in the generative phase (1.278–2.065 mg mL^{-1}). Extracts from rhizomes of

Table 1 Total phenolic content and total antioxidant potential in AEs from different parts of Canadian goldenrod (*S. canadensis*) or giant goldenrod (*S. gigantea*)

<i>S. canadensis</i>			<i>S. gigantea</i>		
Concentration	5%	10%	Concentration	5%	10%
Extract	Mean ± SE		Extract	Mean ± SE	
Total phenolic content—TPC (mg mL ⁻¹)					
Veg ^a	0.724 d ± 0.044	1.187 g ± 0.057	Veg	0.851 e ± 0.025	1.484 i ± 0.079
Gen	0.490 c ± 0.087	1.031 f ± 0.129	Gen	1.278 h ± 0.056	2.065 j ± 0.028
Rhi	0.487 c ± 0.074	0.769 d ± 0.058	Rhi	0.145 a ± 0.022	0.363 b ± 0.015
^b LSD _{0.05}	E: 0.074, C: 0.060, ExC: 0.104		LSD _{0.05}	E: 0.040, C: 0.033, ExC: 0.057	
Total antioxidant potential—TAP (mmol mL ⁻¹)					
Veg	6.299 e ± 0.149	9.441 h ± 0.627	Veg	7.347 f ± 0.295	11.518 i ± 1.216
Gen	2.517 b ± 0.387	4.528 d ± 0.297	Gen	8.270 g ± 1.452	15.308 j ± 0.489
Rhi	3.983 cd ± 0.448	6.665 ef ± 0.701	Rhi	1.607 a ± 0.073	3.331 bc ± 0.154
LSD _{0.05}	E: 0.437, C: 0.357, ExC: 0.618		LSD _{0.05}	E: 0.748, C: 0.611, ExC: 1.058	

^aExtracts from *Solidago* spp. in the vegetative phase are denoted as veg, in the generative phase as gen, and from rhizomes as rhi

^bLSD_{0.05} for the type of extract is denoted as E, for the concentration of extract as C, and for the interaction type of extract and concentration as ExC

both goldenrods, despite the strongest effect of inhibiting *Solidago* growth and development (compare Figs. 1, 2, 3, 4, 5, 6), contained the smallest amount of phenolic compounds (0.145–0.769 mg mL⁻¹). The increase in extract concentration caused a significant increase in TPC.

TAP was strictly connected with TPC (Table 1). Extracts in which the highest TPC was recorded also had the highest TAP, i.e., *S. canadensis*—AEs from plants in the vegetative phase, *S. gigantea*—AEs from plants in the generative phase. Interestingly, in the case of Canadian goldenrod, lower variation in TPC and TAC in the extracts from individual plant parts was denoted than in the case of giant goldenrod.

Stress-related phytohormones and benzoic acid content in extracts

A significantly higher ABA content in AEs from *S. canadensis* and *S. gigantea* in the vegetative phase was recorded, compared to other extracts from both goldenrods (Table 2). ABA content in AEs from Canadian goldenrod in the vegetative phase at concentration of 5% (282.464 μ g L⁻¹) was over eight times higher than in AEs from rhizomes (33.822 μ g L⁻¹) and over five times higher than in AEs from generative phase (51.106 μ g L⁻¹). In the case of giant goldenrod, similar differences in ABA content from plant parts were observed. The highest ABA content (vegetative phase, concentration 10%) amounted to 293.502 μ g L⁻¹

and the lowest content (rhizomes, concentration 5%)—10.695 μ g L⁻¹. Differences between AEs from various parts of Canadian goldenrod or giant goldenrod in ABA content were significant.

A higher JA content was recorded in AEs from Canadian goldenrod and giant goldenrod in the generative phase, in comparison to other treatments (Table 2). For Canadian goldenrod it ranged between 37.924 and 98.676 μ g L⁻¹, for giant goldenrod—127.487–210.637 μ g L⁻¹.

Similarly to ABA, the highest SA content was noted in AEs from *S. canadensis* and *S. gigantea* in the vegetative phase (Table 2). It was in the range of 1632.086–2177.545 μ g L⁻¹ or 492.494–794.833 μ g L⁻¹, respectively. SA content in Canadian goldenrod AEs was several times higher than in giant goldenrod AEs (excluding rhizomes extracts). Differences between SA content in AEs from both goldenrod species were significant. The lowest content of all stress-related phytohormones (ABA, JA, and SA) was recorded in the rhizomes AEs.

BeA content in AEs differed depending on plant species, plant part and extract concentration (Table 2). For Canadian goldenrod, a significantly higher BeA content was noted in AEs from rhizomes (246.987–438.903 μ g L⁻¹), in comparison to extracts from other goldenrod parts. For giant goldenrod, the highest BeA content was observed in AEs in the generative phase (123.554–218.782 μ g L⁻¹).

Table 2 Content of stress-related phytohormones—abscisic, jasmonic and salicylic acids, and benzoic acid in AEs from different parts of Canadian goldenrod (*S. canadensis*) or giant goldenrod (*S. gigantea*)

<i>S. canadensis</i>			<i>S. gigantea</i>		
Abscisic acid – ABA (µg L ⁻¹)					
Concentration	5%	10%	Concentration	5%	10%
Extract	Mean ± SE		Extract	Mean ± SE	
Veg	282.464 f ± 12.659	361.425 g ± 17.019	Veg	175.757 e ± 19.140	293.502 f ± 68.502
Gen	51.106 bc ± 3.138	114.394 d ± 24.873	Gen	38.828 ab ± 1.271	75.205 c ± 15.981
Rhi	33.822 ab ± 1.896	71.302 c ± 8.111	Rhi	10.695 a ± 0.419	27.799 ab ± 2.401
LSD _{0.05}	E: 12.766, C: 10.424, ExC: 18.054		LSD _{0.05}	E: 27.489, C: 22.445, ExC: 38.875	
Jasmonic acid–JA (µg L ⁻¹)					
Concentration	5%	10%	Concentration	5%	10%
Extract	Mean ± SE		Extract	Mean ± SE	
Veg	46.527 c ± 2.263	53.592 c ± 5.073	Veg	38.894 c ± 4.732	49.959 c ± 12.095
Gen	37.924 b ± 3.604	98.676 d ± 27.834	Gen	127.487 e ± 6.340	210.637 f ± 39.786
Rhi	17.041 a ± 1.145	38.917 c ± 4.979	Rhi	8.115 a ± 0.251	20.097 ab ± 0.735
LSD _{0.05}	E: 9.874, C: 8.062, ExC: 13.964		LSD _{0.05}	E: 15.953, C: 13.025, ExC: 22.561	
Salicylic acid–SA (µg L ⁻¹)					
Concentration	5%	10%	Concentration	5%	10%
Extract	Mean ± SE		Extract	Mean ± SE	
Veg	1632.086 g ± 114.470	2177.545 h ± 97.381	Veg	492.494 bc ± 33.171	794.833 e ± 167.911
Gen	1147.119 f ± 154.189	2211.813 h ± 513.818	Gen	350.821 ab ± 29.236	702.890 de ± 107.792
Rhi	321.843 ab ± 35.622	591.471 cde ± 22.814	Rhi	213.421 a ± 15.344	432.382 bc ± 13.138
LSD _{0.05}	E: 210.531, C: 171.898, ExC: 297.736		LSD _{0.05}	E: 77.386, C: 63.185, ExC: 109.440	
Benzoic acid–BeA (µg L ⁻¹)					
Concentration	5%	10%	Concentration	5%	10%
Extract	Mean ± SE		Extract	Mean ± SE	
Veg	111.981 cd ± 5.274	156.249 e ± 4.293	Veg	97.072 c ± 4.159	158.704 e ± 31.215
Gen	61.859 b ± 7.169	117.869 cd ± 27.855	Gen	123.554 d ± 0.934	218.782 f ± 30.246
Rhi	246.987 g ± 44.050	438.903 h ± 16.298	Rhi	27.306 a ± 1.350	66.727 b ± 3.427
LSD _{0.05}	E: 20.911, C: 17.074, ExC: 29.573		LSD _{0.05}	E: 16.515, C: 13.485, ExC: 23.356	

The abbreviations as in Table 1

Damages caused by extracts to aboveground parts of *Solidago* spp.

The greatest damages to aboveground parts of *S. canadensis* and *S. gigantea* were caused by AEs from rhizomes, as recorded at two and ten days after spraying (Figs. 1, 2, 3, 4).

The damages after application of AEs from rhizomes were in the range of 29–50% and 22–40% for *S. canadensis* and *S. gigantea*, respectively. The increase in AE concentration caused an increase in the damaged area but it was not always significant (refers to extracts from all plant parts). For both goldenrod species after spraying with AEs, regardless of their concentration, the damaged area increased over time.

Aboveground and belowground biomass of *Solidago* spp.

Most of the AEs, used in the experiment reduced the above- and belowground biomass of Canadian goldenrod and giant goldenrod (Figs. 5, 6). Canadian goldenrod proved to be more susceptible to the biomass-limiting effect of AEs. For all extracts, which were foliar sprayed on this species, a significant decrease in aboveground biomass was recorded. It ranged between 19 and 42%, compared to the control. The most effective in limiting the aboveground biomass of Canadian goldenrod was an extract from its rhizomes. It caused a 34–42% reduction in biomass, compared to the control,

Fig. 1 Damages to aboveground parts of Canadian goldenrod (*S. canadensis*) and giant goldenrod (*S. gigantea*) with AEs prepared from different parts of goldenrods 2 DAS. *Means with different letters are significantly different, according to Fischer test; the other abbreviations as in Fig. 1

Fig. 2 Damages to aboveground parts of Canadian goldenrod (*S. canadensis*) and giant goldenrod (*S. gigantea*) with AEs prepared from different parts of goldenrods 10 DAS. The abbreviations as in Fig. 1

and the greatest damages to aboveground parts of plants (compare Figs. 1, 2). The extract from Canadian goldenrod rhizomes also caused a significant reduction of belowground biomass (on average 25%). In the case of *S. gigantea*, after applying rhizomes AEs, a significant decrease in aboveground biomass was noted only at a concentration of 10%—on average 24%, compared to control.

Correlation analysis

No significant correlation between the damages to aboveground parts of *S. canadensis* and *S. gigantea* and most of the assessed compounds in AEs (i.e., TPC, TAP, ABA and, only in the case of *S. gigantea*—SA and BeA) were

recorded (Tables 3, 4). There was a highly positive correlation between TPC and TAP, SA content, JA content (for *S. canadensis* and *S. gigantea*). A positive correlation was also found between TPC and ABA content. In the case of both goldenrod species, a significant correlation was recorded between the damages to aboveground parts observed on the second and tenth DAS. The damaged area of aboveground plant parts 2 DAS was very highly correlated with the damaged area of aboveground parts 10 DAS. Neither for *S. canadensis* nor for *S. gigantea* there was a correlation between damages 2 or 10 DAS and the above- and belowground biomass. A high positive correlation between the aboveground biomass and belowground biomass of *S. gigantea* was observed.

Fig. 3 Aboveground parts of giant goldenrod (*S. gigantea*) foliar-sprayed with extracts prepared from plants in generative phase at concentration 5%, 10 days after spraying

Fig. 4 Aboveground parts of giant goldenrod (*S. gigantea*) foliar-sprayed with extracts prepared from rhizomes at concentration 10%, 10 days after spraying

Discussion

Biochemical composition of extracts

Many authors have attempted to analyze the chemical composition of extracts or essential oils (EOs) obtained from different parts of *S. canadensis* and *S. gigantea* (Thiem et al. 2001; Gruľová et al. 2016; Elshafie et al. 2019). In addition, the chemical content of preparations from the species native to Poland, i.e. *S. virgaurea*, is often studied (Kähkönen et al. 1999; Thiem et al. 2001; Demir et al. 2009). However, there are a few research results concerning phenolic compounds content in AEs of *S. canadensis* and *S. gigantea* (Kołodziej et al. 2011; Radusiene et al. 2015) and also the antioxidant potential associated therewith (Deng et al. 2015). Phenolic compounds, especially phenolic acids, are one of the most important substances responsible for autoallelopathic effects (Chon and Kim 2002; Chon et al. 2002).

Different authors showed different results regarding TPC in extracts from goldenrods species. Baležentienė (2015) analyzed TPC in Canadian goldenrod AEs prepared in four concentrations (0.02; 0.05; 0.1 and 0.2%) from various parts of *S. canadensis* at rosette, flowering and maturity stages. The highest TPC was observed in AEs from leaves at flowering and the lowest—in Canadian goldenrod seeds. Deng et al. (2015) recorded the higher TPC in AEs from leaves of *S. canadensis* compared to those from barks. Additionally, the same researchers observed the higher TPC in extracts of goldenrod harvested at the full blooming stage than in the vegetative growth stage (Deng et al. 2015). In our study, the highest TPC for *S. canadensis* was noted in the extracts from leaves and shoots collected during the shoot development phase. In the case of *S. gigantea*—in the extracts from plant parts harvested at flowering. Radusiene et al. (2015) compared the accumulation of phenolic compounds in methanolic extracts from leaves and inflorescences of *S.*

Fig. 5 An average fresh biomass of aboveground parts of Canadian goldenrod (*S. canadensis*) or giant goldenrod (*S. gigantea*) 21 DAS with AEs prepared from different parts of goldenrods. The abbreviations as in Fig. 1

Fig. 6 An average fresh biomass of belowground parts of Canadian goldenrod (*S. canadensis*) or giant goldenrod (*S. gigantea*) 21 DAS with AEs prepared from different parts of goldenrods. The abbreviations as in Fig. 1

canadensis and *S. gigantea*. The authors found that, similar to our results, Canadian goldenrod and giant goldenrod extracts contained different amounts of phenolic compounds. *S. gigantea* had significantly more of the majority of investigated compounds, compared to *S. canadensis*. Our results, as well as the results of other authors (Thiem et al. 2001; Demir et al 2009; Kołodziej et al. 2011; Bach et al. 2015), confirmed, that the content of phenolic compounds in plants depends on the plant species, part of the plant and the extraction method.

According to Kähkönen et al. (1999), many phenolic compounds are commonly distributed in different plant parts and exhibit, e.g., antioxidant, antimicrobial or anti-inflammatory

properties. The important role of phenolic compounds as a major determinant of antioxidant potential is pointed out by Balasundram et al. (2006). The results of our experiment confirmed, that TPC is highly positively correlated with total antioxidant potential (TAP).

It should be noted that the biochemical composition of the raw extract is very complex and compounds profiled by the authors are only the groups selected in the course of the presented experiments. The *Asteraceae* family is also a source of other potent allelopathic mainly polyacetylene compounds (Konovalov 2014). However, taking into account the process of preparation of the extract (24 macerations in water), the extraction yield of polyacetylenes is rather low

Table 3 Relationships between observed traits based on Pearson's correlation coefficients for Canadian goldenrod (*S. canadensis*)

<i>S. canadensis</i>	Damages2d	Damages10d	TPC	TAC	SA	ABA	BeA	Aboveground biomass	Belowground biomass	JA
Damages2d*	1									
Damages10d	0.9129***	1								
TPC	-0.3049	-0.2848	1							
TAP	-0.0917	-0.0797	0.7176***	1						
SA	-0.3977*	-0.3933*	0.772***	0.3934*	1					
ABA	-0.2673	-0.2885	0.6716***	0.7976***	0.7032***	1				
BeA	0.4048*	0.4617*	-0.038	0.2646	-0.5549**	-0.2907	1			
Aboveground biomass	-0.2293	-0.2167	0.1327	0.1131	0.3602	0.4283*	-0.4668**	1		
Belowground biomass	-0.2869	-0.2804	0.2504	0.1924	0.3143	0.3602	-0.2423	0.2786	1	
JA	-0.2807	-0.2499	0.6463***	0.1065	0.8051***	0.2501	-0.2893	0.017	0.1867	1

Damages 2 days after spraying are denoted as damages2d; damages 10 days after spraying as damages10d; total phenolic content as TPC; total antioxidant potential as TAP; salicylic acid as SA; abscisic acid as ABA; jasmonic acid as JA; benzoic acid as BeA

Significant differences: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 4 Relationships between observed traits based on Pearson's correlation coefficients for giant goldenrod (*S. gigantea*)

<i>S. gigantea</i>	Damages2d	Damages10d	TPC	TAP	SA	ABA	BeA	Aboveground biomass	Belowground biomass	JA
Damages2d	1									
Damages10d	0.9298***	1								
TPC	-0.1858	-0.2101	1							
TAP	-0.1568	-0.194	0.9844***	1						
SA	-0.0118	-0.079	0.7299***	0.7812***	1					
ABA	-0.0159	-0.1666	0.3948*	0.46*	0.7689***	1				
BeA	-0.1523	-0.1653	0.9606***	0.954***	0.8263***	0.4347*	1			
Aboveground biomass	-0.262	-0.25	0.0586	0.0679	0.0893	0.0381	0.1063	1		
Belowground biomass	-0.2319	-0.1517	-0.0979	-0.1171	-0.2058	-0.2654	-0.0575	0.7566***	1	
JA	-0.194	-0.1252	0.8489***	0.7961***	0.4369*	-0.0661	0.8471***	0.1093	0.0772	1

The abbreviations as in Table 3

knowing their low polarity and thus low solubility in pure water. Another mention-worthy problem is also related to the method of extract preparation, under non-sterile conditions over 24 h. It is possible that some active compounds or compound groups were degraded or converted to other forms. This problem should be taken into account in further experiments. However, Dordevic et al. (2019) showed that microbial interaction could lead to the increased content of total phenolics and flavonoids. In the case of our extracts, it could be expected that possible microbial interaction, as well as activation of rests of the endogenous enzymatic system, improved the solubilization of some allelopathic compounds and leads to the cleavage of others. It could be assumed that phenolic compounds could be here an example.

Allelopathic and autoallelopathic potential of *Solidago* spp.

The results of our research confirmed the effect of allelopathic extracts from goldenrods on the growth and development of goldenrods themselves. AEs from plant parts collected at shoot development or flowering stage inhibited the increase in above- and belowground biomass of Canadian and giant goldenrod. However, the difference was not always significant in comparison to the control. According to Sołtys et al. (2010), plants that exhibit autoallelopathic potential may use self-produced phytotoxins to control their species' population over time and space. This strategy of eliminating competitors is perfectly visible in the almost one-species communities produced by goldenrods (Szymura and Szymura 2015). No reports about the autoallelopathic effect of goldenrod have been found in the literature.

Nevertheless, many authors highlighted the allelopathic nature of compounds found in extracts from Canadian goldenrod and giant goldenrod (Bing-Yao et al. 2006; Abhilasha et al. 2008; Shen et al. 2008; Yuan et al. 2013), which may influence the growth and development of other plant species and microorganisms coexisting with them. For instance, in laboratory and pot experiments, Baličević et al. (2015) assessed the allelopathic effect of AEs from aboveground parts of *S. gigantea* on plants' growth and development. The authors reported that allelopathics found in extracts from giant goldenrod inhibited germination and growth of weeds, i.e., redroot amaranth (*Amarantus retroflexus* L.) and velvetleaf (*Abutilon theophrasti* Medik.), more effectively than the crops—winter barley (*Hordeum vulgare* L.), common carrot (*Daucus carota* L.) and coriander (*Coriandrum sativum* L.). Sekutowski et al. (2012) obtained results pointing on both inhibiting and stimulating effects of the AEs from leaves and stems of giant goldenrod on common buckwheat (*Fagopyrum esculentum* Moench) and sunflower (*Helianthus annuus* L.). The authors reported that examined extracts

significantly decreased the germination capacity and average length of buckwheat embryonic roots.

On the other hand, Bing-Yao et al. (2006) assessed the potential role of allelopathic compounds of Canadian goldenrod in colonizing new land. Researchers established that most extracts from Canadian goldenrod inhibit germination and initial growth of common wheat (*Triticum aestivum* ssp. *vulgare*), Chinese cabbage (*Brassica campestris* L.), and white mulberry (*Morus alba* L.). Our research results, indicating that bioactive substances in aboveground parts of *S. canadensis* may inhibit the development of other plants, are in agreement with the results by Kieć and Wieczorek (2009). Authors found that decoctions from aboveground parts of Canadian goldenrod contributed to reducing the length and mass of lambsquarters (*Chenopodium album* L.).

Conclusions

The aqueous extracts (AEs) prepared from different Canadian goldenrod and giant goldenrod plant-parts exhibit inhibitory, autoallelopathic properties against the goldenrod species in early developmental stages. The content of phenolic compounds, antioxidants, selected phytohormones in AEs and their autotoxic effect, differ depending on plant species, plant parts and extract concentration. In *S. canadensis*, the highest content of phenolics and antioxidants is observed in the AEs from vegetative parts of plants. In the case of *S. gigantea*—in extracts from plants in generative phase. For both goldenrod species, the highest content of ABA and SA was found in AEs from plants collected during vegetative growth. However the initial growth and development of goldenrods are limited the most effectively by extracts prepared from rhizomes. They cause damages to aboveground parts in the range 22–50% and significantly reduce their above- and belowground biomass in the range 7–42% and 12–24% relative to control, respectively. *S. canadensis* and *S. gigantea* show different susceptibility to the influence of autotoxic substances. Canadian goldenrod is more susceptible to the effect of autotoxins, as manifested by greater damages of aboveground parts and reduction in above- and belowground biomass. Between all examined chemical compounds and the damages to aboveground parts of both goldenrods no significant correlations were found. There were also no significant correlations between the assessed compounds in AEs and the above- and belowground biomass of *S. canadensis* and *S. gigantea*. Therefore, further research is needed to identify the substances responsible for the autoallelopathic effect of AEs obtained from different parts of goldenrods.

Author contribution statement DG-C designed and carried out the experiment and wrote the manuscript; MD performed biochemical analysis of the extracts and participated in writing the paper; JB carried out statistical analysis and participated in writing the paper; AS designed the experiment and participated in writing the paper.

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