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ESTIMATION OF SPECIES ALLELOPATHIC SUSCEPTIBILITY TO PERENNIAL WEEDS BY DETAILING THE FORMATION PERIOD OF GERMINATED SEEDS OF OILSEED RADISH (*Raphanus sativus* L. var. *oleiformis* Pers.) AS THE TEST OBJECT

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ABSTRACT. The allelopathic impact of 23 perennial weed species on oilseed radish by petri dish and soil bioassays was studied. Weed extracts were prepared at concentrations of 0.25, 0.5, 1.0, 2.0, 4.0, 8.0 and 16.0%. The influence of the weed extract on germination and seedling growth of oilseed radish was analyzed according to several germination indexes. The "speed of germination", "coefficient of the velocity of germination" and the resulting levels of allelopathic potential in terms of seed germination (APG) were used to assess the allelopathic effect of the researched weed species. The application of indicators allowed determining the specific features of the influence of extracts of perennial weeds on the duration of the germination period, the effects of germination delay and the general prolongation of the period of formation of similar seeds with typification on classification groups. Conducted daily surveys for the calculation of these indices allowed to obtain a graphical interpretation of the reaction of the seeds of the test object to the extract of each weed species. This allowed identifying species of weeds for which the use of oilseed radish in the system of its biological control will be effective.

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Introduction

The level of weediness of agrocenoses within their growth, development and crop formation, and the potential one due to the accumulation of weed seeds in the soil is one of the potential threats to reducing the yield of major crops and efficiency of world agricultural production (Chauan, 2020; Shahzad *et al.*, 2021). The negative impact of weeds on crops is observed in the form of competition for resources and allelopathic interaction of plants (Scavo *et al.*, 2019; Sharma *et al.*, 2019, 2021; Bachheti *et al.*, 2020; Clapp, 2021). Weeds have serious impacts on agricultural production. It is estimated that in general weeds cause a 5% loss in agricultural production in most developed countries, 10% loss in less developed countries and 25% loss in the least developed countries (Gharde *et al.*, 2018; Mesterházy *et al.*, 2020). Perennial weeds using their own high biological, adaptive and allelopathic potential (Travlos *et al.*, 2018; Ackroyd *et al.*, 2019; Romaneckas *et al.*, 2021) are rather harmful. It's have a high levels of competitiveness in relation to the main crop species (Melander *et al.*, 2016; Bergkvist *et al.*, 2017; Novak *et al.*, 2018), and demonstrate high plasticity of development (Bybee-Finley *et al.*, 2017; Somerville *et al.*, 2018). Perennial weeds are also characterized by high fertility and long-term viability of vegetative and seed germs in the soil (Haring, Flessner, 2018). These species are also characterized by rapid rates of spread (Możdżeń *et al.*, 2018), high levels of adaptation to modern climate change and levels of tillage technologies (Travlos *et al.*, 2018; Simić *et al.*, 2020). All this leads to high biological competitiveness of perennial weed species (Buddhadeb, Bhowmik, 2020; Kocira, Staniak, 2021).

The modern strategy of integrated weed control has branch combining effective phytocenological construction of agrocenosis taking into account the allelopathic interaction of species forming it (Westwood *et al.*, 2018; Anwar *et al.*, 2019; Korresa *et al.*, 2019; MacLaren *et al.*, 2020; Schandry, Becker, 2020; Muli *et al.*, 2021). It meets environmental friendliness and organicity of relevant cultivation technologies, and the ability to mobilize natural factors of plant adaptation to competition with other species due to its allelopathic potential (Jugulam *et al.*, 2019; Kumar *et al.*, 2020). Under these conditions, the use of plants with high allelopathic potential with the main species of weeds will reduce the level of herbicide load due to substances of allelochemicals with a corresponding herbicidal effect (Kaab *et al.*, 2020; Maurya *et al.*, 2022). Enhancement of the bioherbicidal effect is due to the content of complex active allelochemicals, including essential oils of different chemical structures (Mirmostafaee *et al.*, 2020; Gharibvandi *et al.*, 2022). On the other side, the allelopathic potential of cruciferous crops is widely known and successfully used in the system of greening, binary and mixed crops, biofumigation, soil remediation, and phytoremediation (Ali *et al.*, 2019; Khan *et al.*, 2019; Rehman *et al.*, 2019; Koehler-Cole *et al.*, 2020; Tsytsiura, 2020; Rasul, Ali, 2020, 2021; Liu *et al.*, 2021). However, the complex aspects of the interaction of cruciferous plant species with perennial species taking into account their allelopathic potential is an issue that requires additional scientific generalization and study. This is relevant for oilseed radish, which is widely used in agronomic practice in the system of greening and organic farming (Ferreira *et al.*, 2021). However, it should be noted that the research of plant species" allelopathic sensitivity as a basic one involves the assessment of germination under the influence of other species" extracts (Kobayashi *et al.*, 2021). According to Sothearith *et al.* (2021), germination is an informative indicator of allelopathic sensitivity, but many features require more careful research. The working hypothesis of our research is the possibility of studying the allelopathic reaction of the test object at the stage of its germination by estimating the rate of its formation and options for prolonging the germination from the optimal dates. This detail will clarify their impact on the stages of seed germination and the nature of the biological response of the test object to aggressive allelopathic species. This version of the study of allelopathy differs from traditional methods in terms of seed germination.

Materials and Methods

Study Site: This research was performed in May-August 2020 at Vinnytsia National Agrarian University (49°11′ N, 28°22′ E), during the oilseed radish growing season of April-September (sowing date April 12–15, harvest date September 5–10). Height above sea level: 325 m. The area has a temperate continental climate. During the study period, the maximum and minimum temperatures were 18.3 °C in July and 15.8 °C in May, respectively. Mean annual relative humidity was 77% and mean annual precipitation was 480–596 mm.

Selection of the perennial weed species: the frequency of appearance (F) of perennial weeds was investigated from 2013 to 2020 in the oilseed radish fields located at the Vinnytsia National Agrarian University (Table 1).

Oilseed radish was sown at densities comprised between 0.5 and 4.0 million seeds ha^{-1} in 25 plots with a size of 1.0 x 1.0 m in two non-contiguous variants of the density of standing oilseed radish. Each year, quadrants of 1 m^2 were randomly thrown in 50 different locations in each oilseed radish plot at the starting fruiting phase BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemical industry) 70–74.

Table 1. The botanical name, English name, family and economic importance of the perennial weed species involved in this study

No.	Botanical name	EPPO code	English name	Family	Frequency (F)***
1	*Achillea millefolium* L.	ACHMI	Common yarrow	Asteraceae	1.8*–4.1**
2	*Acroptilon repens* (L.) de Candolle	CENRE	Russian knapweed	Asteraceae	12.6–31.4
3	*Agropyron repens* (L.) Gould	AGRRE	Couch grass	Poaceae	50.8–71.3
4	*Arctium lappa* L.	ARFLA	Greater burdock	Asteraceae	1.3–2.9
5	*Artemisia absinthium* L.	ARTAB	Wormwood	Asteraceae	4.5–3.7
6	*Artemisia vulgaris* L.	ARTVU	Common mugwort	Asteraceae	5.4–3.6
7	*Carduus acanthoides* L.	CRUAC	Spiny plumeless thistle	Asteraceae	6.7–10.3
8	*Cichorium intybus* L.	CICIN	Common chicory	Asteraceae	1.8–3.9
9	*Cirsium arvense* (L.) Scopoli	CIRAR	Creeping thistle	Asteraceae	40.7–48.9
10	*Convolvulus arvensis* L.	CONAR	Field bindweed	Convolvulaceae	17.9–25.8
11	*Cuscuta campestris* Yuncker	CVCCA	Field dodder	Convolvulaceae	1.3–2.9
12	*Cyclachaena xanthiifolia* Nuttall	IVAXA	Giant sumpweed	Asteraceae	5.2–12.3
13	*Cynodon dactylon* (L.) Pers.	CYNDA	Bermuda grass	Poaceae	10.1–15.8
14	*Echium vulgare* L.	EHIVU	Blueweed	Boraginaceae	1.9–5.8
15	*Equisetum arvense* L.	EQUAR	Field horsetail	Equisetaceae	3.9–12.3
16	*Linaria vulgaris* Mill.	LINVU	Yellow toadflax	Plantaginaceae	4.2–7.5
17	*Onopordum acanthium* L.	ONRAC	Cotton thistle	Asteraceae	1.3–1.9
18	*Plantago lanceolata* L.	PLALA	Narrowleaf plantain	Plantaginaceae	2.6–3.1
19	*Plantago major* L.	PLAMA	Broadleaf plantain	Plantaginaceae	3.8–5.5
20	*Rumex acetosella* L.	RUMAA	Field sorrel	Polygonaceae	2.1–4.4
21	*Rumex confertus* Willdenow	RUMCF	Russian dock	Polygonaceae	1.7–2.9
22	*Sonchus arvensis* L.	SONAR	Field sowthistle	Asteraceae	27.8–36.1
23	*Taraxacum officinale* Weber	TAROF	Common dandelion	Asteraceae	9.8–24.2

* This frequency appeared in oilseed radish fields sown with 0.5 million seeds ha^{-1}; ** this frequency appeared in oilseed radish fields sown with 4.0 million seeds ha^{-1}; *** average indicators for the period 2013–2020.

Individuals of each weed species in each quadrant were identified with the aid of standard flora reference books (Veselovsky *et al.*, 1988). Then, the Frequency (F) for a weed species was yearly calculated by Eq. (1). (Rana, Rana, 2016; Rao, 2017):

$$F(\%) = \frac{TOI}{50} \cdot 100, \qquad (1)$$

where TOI is the number of squares at which a weed species appeared.

Extract preparation: The whole plants (aerial and underground parts) of 23 weed species selected according to the F values were collected at the flowering stage in Fromour University''s research fields. The collected plants were transported in air-conditioned vehicles to the laboratory. Before drying, all materials were washed with running water to remove dust and contaminants. After that, plants were partitioned into roots, stems, leaves and inflorescences and were hand cut into small pieces of 2–3 cm long. Then, they were dried in the shade at 27–30 °C for 11 days. The dried samples were powdered using a laboratory mill and stored in sealed bags in a dry place in the dark.

Extracts were prepared by immersion of each powdered sample into heated distilled water at 40 ºC for 24 h (Grodzinsky *et al.*, 1990; Grodzinsky, 1991). Weights of 0.625, 1.25, 2.5, 5, 10, 20 and 40 g of each powdered plant material were immersed in flasks containing 250 ml of distilled water to obtain concentrations of 0.25, 0.5, 1, 2, 4, 8 and 16%, respectively. The flasks were shaken by hand every two hours. After heating, extracts were recovered by centrifugation at 4000 rpm and 30 ºC for 30 s in a centrifuge Eppendorf model 5804R. Thereafter, the extracts were filtered through Whatman Filter paper No. 1.

Petri plate bioassays: they were performed in a complete randomized design with three factors which were (i) the weed species (23 species), (ii) the weed parts (root, stem, leaf and flower), and (iii) extract concentration (0.25, 0.5, 1, 2, 4, 8 and 16%). Fifty oilseed radish seeds were sown on filter paper in each petri dish. Then, 50 mL of an aqueous extract was added to each petri dish. Extract concentrations (0.25, 0.5, 1, 2, 4, 8 and 16%) were tested. Each extract concentration was replicated 4 times and the experiments were performed twice. The control consisted of distilled water added instead of the water extracts. The Petri plates were kept in a Biological Oxygen Demand (BOD) incubator at 25 °C and seed germination was recorded on the 6th day (AOSA Rules for Testing Seeds, 2011; ISTA, 2017; Jain *et al.*, 2017). Speed of germination was recorded daily until the 6th day (Duke, 2015).

Collection of rhizosphere soil: The rhizosphere soil of the 23 weed species was directly collected (Fujii *et al.*, 2005). The weed species were taken out from the soil without disturbance, then plant roots were shaken softly to remove the root-zone soil. Each soil sample was sieved through a 1 mm mesh to remove coarse particles (root hair, *etc*.). Then, the sieved soil samples were immediately used in bioassays (Williamson, Richardson, 1988; Grodzinsky *et al.*, 1990; Grodzinsky, 1991). In all cases, the collected soil samples were classified as dark grey forest Luvic Greyic Phaeozem soils (IUSS Working Group, 2015; State standard of Ukraine ISO (International Organization for Standardization) 10381-6:2015, 2017) with 2.56% organic carbon, 77.9 kg ha^{-1} lightly hydrolyzed nitrogen, 153 kg ha^{-1} mobile phosphorus, 105 mg kg^{-1} exchangeable potassium and pH_{KCl} 6.0.

Soil bioassays: they also were performed in a complete randomized design with three factors. Plastic 150-well-plates were used where each well had a depth of 7 cm, an upper diameter of 4.2 cm, and a lower diameter of 1.7 cm. Each well was filled with 65 g of fresh rhizosphere soil. Then, each well was irrigated with 30 mL of distilled water. After 2 h, the seeds were sown in the centre of each well. Seeds were placed at 2 cm depth. The 20 mL aqueous extracts of weeds/water (Control treatment) per well were added on 1.5 and 10 days after germination. One treatment had 10 wells and all treatments were replicated 5-times.

Indicators such as speed of germination (S) and coefficient of the velocity of germination (CV_i) were used to determine the peculiarities of seed germination by the action of the corresponding weed extracts.

The speed of germination (S) was calculated by the Eq. (2) (Duke, 2015) taking into account (ISTA, 2017):

$$S = \frac{N_1}{1} + \frac{N_2}{2} + \frac{N_3}{3} \ldots \frac{N_n}{n}, \qquad (2)$$

where, N_1, N_2, $N_3 \ldots N_n$, ... are the number of seeds germinated on days 1, 2, 3...n.

Coefficient of the velocity of germination (CV_i (% day^{-1})) in percentage terms (own interpretation of the Abd El-Gawad formula (2014)) was recorded daily till the 9th day and was calculated by the Eq. (3):

$$CV_i = \left(\frac{\sum N_i}{T} \right) \times 100, \qquad (3)$$

where, N – number of seeds germinated on day and T – the total number of seeds laid in the variant for germination.

The traditional block of allelopathic evaluation of seed germination indicators included a number of typical indicators.

Allelopathic potential was calculated for seed germination (APG) Allelopathic potential was determined by the Eq. (4) (Rueda-Ayala *et al.*, 2015).

$$APG = ((IR_a + IR_b)/2)/100, \qquad (4)$$

where, APG – allelopathic potential of gemination; IR_a and IR_b – germination inhibitions recorded at weed extract concentrations of 1 and 4%, respectively.

Per cent inhibition (IR) was calculated according to Eq. (5) (Marinov-Serafimov, Golubinova, 2015; Marinov-Serafimov *et al.*, 2017, 2019):

$$IR = \frac{C - T}{C} \times 100, \tag{5}$$

where C – germination in control and T – germination in a treatment.

The seed germination (%) was calculated after preliminary arcsin-transformation following Eq. (6) (Marinov-Serafimov *et al.*, 2017, 2019):

$$Y = arcsin\left(\sqrt{\frac{x\%}{100}}\right), \tag{6}$$

Basic statistical data analysis was done with Microsoft Office Excel 2010. Figures were constructed with Microsoft Office Excel 2010 and Tukey multiple comparisons of means 95% family-wise confidence level were performed with the R-statistica (i386 3.2.2) and the application of proven methods of biometric statistics (Sokal, James, 2012; Rumsey, 2016).

Results and Discussion

Long-term research on oil radish coenosis weediness (Tsytsiura, 2020) showed the complex nature of its formation both in terms of species composition and the nature of the individual species dominance (Table 1). The share of the Asteraceae family species accounts for 52.2%, they are dominant in the agrocenosis of oilseed radish. Other species are placed in descending order of their coenotic role, *i.e.*, Plantaginaceae (13.1%), Convolvulaceae, Poaceae, Polygonaceae (8.7%), Boraginaceae, Equisetaceae (4.3%). The species obtained ratio by biological features allows classifying the type of perennial species weedings of perennial species of oilseed radish agrocenoses as the root-sprouting and rhizome type.

The oilseed radish seeds germination in "petri dish bioassay" (Table 2) showed a specific species allelopathic sensitivity of oilseed radish. It is confirmed by laboratory germination results both in water and soil substrate already from the extract concentration level of 0.25%. For most of the studied species, the concentration of 4.0% extract was indicative. Increasing its value to 8 and 16% led to an intensive decrease in the number of similar seeds of oilseed radish by the action of extracts of 16 species of weeds and its complete absence by the action of extracts of 8 species.

According to Grodzinsky (1992), this nature of reaction indicates both high allelopathic sensitivity of the species and its adaptive vitality tactics in the formation of its cenosis in the overall cenosis of interactions between species diversity of competing plant species. In many studies (Jabran *et al.*, 2015; Kunz *et al.*, 2016; Lahdhiri, Mekki, 2016), an allelopathic reaction in the range from 0.1% to 32.0% was observed for many plant species.

Table 2. Seed germination of oilseed radish exposed to aqueous extracts prepared ("Petri dish bioassay") from whole plants of 23 perennial weed species

No.	Species of weeds	Germination, % water extracts concentration, %							APG*
		0.25	0.5	1.0	2.0	4.0	8.0	16.0	
1	Control (Distilled water)	92.4	92.7	92.8	93.5	91.4	92.6	93.4	–
2	*Achillea millefolium* L.	90.8^{c}	85.6^{b}	77.6^{a}	58.7^{a}	26.4^{a}	8.2	4.5	0.37
3	*Acroptilon repens* (L.) de Candolle	62.4^{a}	50.2^{a}	32.6^{a}	16.4^{a}	7.3^{a}	0.0	0.0	0.66
4	*Agropyron repens* (L.) Gould	78.9^{a}	60.9^{a}	42.2^{a}	26.2^{a}	10.4^{a}	1.8	0.0	0.60
5	*Arctium lappa* L.	89.6^{b}	84.2^{b}	72.6^{a}	56.4^{a}	10.4^{a}	1.7	0.0	0.48
6	*Artemisia absinthium* L.	86.1^{b}	70.3^{a}	57.8^{a}	27.8^{a}	11.3^{a}	2.4	0.0	0.53
7	*Artemisia vulgaris* L.	86.7^{b}	73.6^{a}	60.3^{a}	36.5^{a}	17.5^{a}	3.1	0.0	0.49
8	*Carduus acanthoides* L.	76.2^{a}	70.8^{a}	62.6^{a}	49.3^{a}	27.2^{a}	1.4	0.0	0.43
9	*Cichorium intybus* L.	80.2^{a}	60.8^{a}	42.4^{a}	34.1^{a}	19.4^{a}	2.8	1.5	0.55
10	*Cirsium arvense* (L.) Scopoli	65.9^{a}	48.2^{a}	37.3^{a}	19.1^{a}	9.2^{a}	0.0	0.0	0.63
11	*Convolvulus arvensis* L.	62.8^{a}	50.2^{a}	41.9^{a}	26.7^{a}	9.3^{a}	0.0	0.0	0.61
12	*Cuscuta campestris* Yuncker	60.9^{a}	42.5^{a}	29.3^{a}	16.7^{a}	6.5^{a}	0.0	0.0	0.68
13	*Cyclachaena xanthiifolia* Nuttall	74.1^{a}	60.2^{a}	49.6^{a}	28.6^{a}	11.7^{a}	0.0	0.0	0.56
14	*Cynodon dactylon* (L.) Pers.	82.6^{a}	73.4^{a}	67.2^{a}	29.2^{a}	14.2^{a}	2.7	0.0	0.48
15	*Echium vulgare* L.	82.6^{a}	70.9^{a}	57.8^{a}	36.4^{a}	19.3^{a}	2.7	1.2	0.49
16	*Equisetum arvense* L.	84.7^{b}	71.3^{a}	52.4^{a}	38.8^{a}	5.1^{a}	0.0	0.0	0.60
17	*Linaria vulgaris* Mill.	64.3^{a}	51.7^{a}	37.8^{a}	18.5^{a}	9.3^{a}	1.5	0.0	0.62
18	*Onopordum acanthium* L.	69.7^{a}	59.6^{a}	44.5^{a}	29.5^{a}	12.5^{a}	0.0	0.0	0.58
19	*Plantago lanceolata* L.	77.9^{a}	62.3^{a}	48.4^{a}	29.3^{a}	14.7^{a}	3.6	2.3	0.55
20	*Plantago major* L.	83.9^{b}	62.8^{a}	34.7^{a}	19.2^{a}	8.4^{a}	1.5	0.0	0.64
21	*Rumex acetosella* L.	82.9^{a}	75.3^{a}	62.5^{a}	46.2^{a}	14.7^{a}	2.5	1.4	0.49
22	*Rumex confertus* Willdenow	90.1^{c}	82.6^{a}	78.2^{a}	44.2^{a}	9.6^{a}	1.1	0.0	0.46
23	*Sonchus arvensis* L.	80.2^{a}	67.9^{a}	58.5^{a}	19.2^{a}	7.2^{a}	0.0	0.0	0.56
24	*Taraxacum officinale* Weber	89.5^{b}	84.5^{b}	77.4^{a}	31.5^{a}	18.4^{a}	6.2	2.4	0.41
Tukey multiple comparisons of means 95% family-wise confidence level (the interval of a minimum level of allowable difference for p_{adj})		0.63–0.77	0.79–1.03	0.86–1.12	0.92–1.29	0.96–1.52	–	–	–

Significance levels to control (*p*): a – 0.1%; b – 1%; c – 5%; d – no significant difference.
*APG is the allelopathic potential of gemination oilseed radish calculated for weed extracts concentrations of 1–4%; ** the following classes were considered for the indicator of APG by Smith (2013): 0–0.25 Non-allelopathic (NA); 0.26–0.5 – moderately allelopathic (MA); 0.51–0.75 – highly allelopathic (HA); 0.76–1.0 – extremely allelopathic (EA).

At the same time, the reaction to an intensive decrease in seed germination is already determined from 0.5–1.5%. In some early studies (Inderjit, Keating, 1999), it is noted that the degree of the allelopathic reaction manifestation is conditioned both by the species introduction in terms of the time of its cultivation and by the proximity to typical representatives of weed vegetation. In long-term agricultural use, the species spectrum of allelopathic reaction narrows to the most aggressive species, and vice versa, with limited territorial cultivation, the allelopathic sensitivity is higher. This is confirmed in our studies, given the fact that the intensity of oilseed radish cultivation in many regions is limited. According to Grodzinsky (1991), this nature of reaction indicates both high allelopathic sensitivity of the species and its adaptive vitality tactics in the formation of its cenosis in the overall cenosis of interactions between species diversity of competing plant species. In many studies (Jabran *et al.*, 2015; Kunz *et al.*, 2016; Lahdhiri, Mekki, 2016), an allelopathic reaction in the range from 0.1% to 32.0% was observed for many plant species.

There was a decrease in seed germination at the level of extract concentration in the range of 0.5–1.5%. Some early studies (Inderjit, Keating, 1999) noted that the degree of allelopathic response to the interaction of different species depends on both the date of their introduction and the prevalence of the species in the coenosis. In long-term agricultural use, the species spectrum of allelopathic reaction narrows to the most aggressive species, and vice versa, with limited territorial cultivation, the allelopathic sensitivity is higher. This is confirmed in our studies, given the fact that the intensity of oilseed radish cultivation in many regions is limited. Thereby, the allelopathic threshold for oilseed radish at the seed germination stage for the "Petri dish bioassay" variant reaches 4% of the concentration of the researched perennials extract.

According to Scavo and Mauromicale (2021), such a threshold is identified for assessing the overall level of competition between the studied plant species. The obtained results show significant differences in the species specificity of the seed germination decreased by a multiple of two gradual increases in the weed species extract concentration. Thus, the dynamic decrease in seed germination compared to the concentration of the 0.25% extract was 26.9, 43.4, 71.0, and 86.0% to the previous concentration for *Cirsium arvense* (L.) Scopoli, it was 30.2, 51.9, 72.6 and 89.3% for *Cuscuta campestris* Yuncker and 5.7, 14.5, 35.4 and 70.9% for *Achillea millefolium* L. It should be noted that this decrease has specific features. Naturally, the species with the highest criterion of prevalence in the oilseed radish agrocenosis in terms of F (Table 1) have substantially higher rates of reduced seed germination starting from 1.0% concentration. An intensive decrease of germination is observed in the concentration range of 1.0–2.0% for species with lower occurrence in the agrocenosis, the decrease to the comparable variant of 0.25% may significantly exceed the variant of 4.0%. In our opinion, considering the research results and statements of other scholars (Inderjit, Keating, 1999; Iqbal, Fry, 2012; Melander *et al.*, 2016; Miller, 2016) this impact forms a higher level of allelopathic potential of species with a low presence in the coenosis. This leads to the lack of formation of appropriate coenotic relationships between these species and oilseed radish. On the other hand, these types of weeds belong to the specific content of active allelochemicals and essential oils. As a result, these reasons determine the specificity of the allelopathic reaction at the stage of germination of radish seeds. This specificity, given the content of active allelochemicals, has been pointed out in several recent studies (Chotsaeng *et al.*, 2017; Abd-ElGawad *et al.*, 2021; Gharibvandi *et al.*, 2022).

According to other researchers, it forms an indicator of the species abundance (Rasmussen *et al.*, 2014; Brandsæter *et al.*, 2017; Buddhadeb, Bhowmik, 2020) and provides the possibility of its distribution. If the species" dominance changes in the coenosis, their allelopathic influence on oilseed radish germination will be higher than for traditional species with a high presence in the coenosis (Tsytsiura, 2020). It should also be noted oilseed radish has a lower threshold of sensitivity to aggressive perennial weeds such as *Agropyron repens* (L.) Gould, *Acroptilon repens* (L.) de Candolle, *Carduus acanthoides* L., *Cynodon dactylon* (L.) Pers., *Sonchus arvensis* L. comparing with similar studies on other cruciferous crops (Tollsten, Bergstrom, 1988; Grodzinsky, 1992; Sarmah *et al.*, 1992; Brown, Morra, 1996; Kirkegaard, Sarwar, 1998; Norsworthy, 2003; Turk, Tawaha, 2003; Izzet *et al.*, 2004; Haramoto, Gallandt, 2005; Boydston, Al-Khatib, 2006; Lawley *et al.*, 2011; Morikawa *et al.*, 2012; Awan *et al.*, 2012; Rehman *et al.*, 2012; Takemura *et al.*, 2013; Lemerle *et al.*, 2014; Amini *et al.*, 2014; Harris *et al.*, 2015; Björkman *et al.*, 2015; Ali, 2016; Ali *et al.*, 2019; Khan *et al.*, 2019; Rehman *et al.*, 2019). This factor emphasizes the value of the application of oilseed radish as a sidereal mediator in the system of organic farming technologies.

The nature of the formation of the oilseed radish germination also differed at germination on "petri dish bioassay" and, respectively, in the variant of approximate imitation to field conditions – on "Soil bioassay" (Table 3).

Changing the germination environment of oilseed radish on the soil bioassay reduced the allelopathic effect by 0.2–2.0% depending on the type of weed. The maximum difference is noted when comparing two germination variants in the concentration range of 0.25–2%, and the minimum 1 in the range of 8–16%. Moreover, the value of such reduction is species-specific. Therefore, for the species *Agropyron repens* (L.) Gould 1.1–3.5%, and for the species *Cyclachaena xanthiifolia* Nuttall 1.0–1.8%. This nature of the allelopathic effect has also been noted in the research of several scientists (Fujii *et al.*, 2004; Sturm *et al.*, 2016, 2018; Prinsloo, Plooy, 2018). In these researches, it is explained by the absorption and adsorption of several substances extracted into the solution during the extraction process. This confirms the statement that the allelopathic potential of a particular weed species is determined both by its stage phenological development and by the edaphic conditions of its growth and development, which determine both the vegetation intensity of the species, its vitality index and the degree of influence of its root excretions, given the favourable soil fertility conditions for the species itself.

Table 3. Seed germination of oilseed radish exposed to aqueous extracts prepared (soil bioassay) from whole plants of 23 perennial weed species.

No.	Species of weeds	Germination, % water extracts concentration, %							APG*
		0.25	0.5	1.0	2.0	4.0	8.0	16.0	
1	Control (Distilled water)	91.6	90.3	89.8	90.6	89.2	88.7	90.2	–
2	*Achillea millefolium* L.	90.5[c]	85.3[b]	78.4[b]	60.3[a]	27.8[a]	8.6	5.1	0.34
3	*Acroptilon repens* (L.) de Candolle	63.8[a]	52.6[a]	33.6[a]	15.2[a]	6.8[a]	0.0	0.0	0.65
4	*Agropyron repens* (L.) Gould	82.4[a]	63.8[a]	44.6[a]	32.8[a]	12.8[a]	2.9	0.0	0.56
5	*Arctium lappa* L.	90.4[c]	85.6[b]	73.9[a]	57.8[a]	11.8[a]	2.1	0.0	0.44
6	*Artemisia absinthium* L.	87.4[c]	71.8[a]	62.1[a]	30.9[a]	12.6[a]	3.7	0.0	0.49
7	*Artemisia vulgaris* L.	87.9[c]	74.5[a]	62.4[a]	39.3[a]	19.8[a]	4.0	0.0	0.45
8	*Carduus acanthoides* L.	80.2[a]	75.3[a]	69.5[a]	51.8[a]	33.5[a]	2.1	0.0	0.35
9	*Cichorium intybus* L.	81.7[a]	62.3[a]	44.5[a]	35.6[a]	19.8[a]	3.2	1.8	0.52
10	*Cirsium arvense* (L.) Scopoli	68.9[a]	53.6[a]	44.7[a]	23.8[a]	15.2[a]	0.0	0.0	0.54
11	*Convolvulus arvensis* L.	64.8[a]	52.6[a]	43.5[a]	30.4[a]	11.6[a]	0.0	0.0	0.57
12	*Cuscuta campestris* Yuncker	56.4[a]	40.3[a]	28.4[a]	15.2[a]	5.8[a]	0.0	0.0	0.68
13	*Cyclachaena xanthiifolia* Nuttall	75.6[a]	62.3[a]	50.9[a]	29.8[a]	12.6[a]	0.0	0.0	0.53
14	*Cynodon dactylon* (L.) Pers.	83.9[b]	77.2[a]	74.3[a]	34.5[a]	19.2[a]	3.2	0.0	0.40
15	*Echium vulgare* L.	83.8[b]	72.5[a]	59.6[a]	35.6[a]	18.4[a]	2.3	1.0	0.47
16	*Equisetum arvense* L.	80.4[a]	70.6[a]	51.2[a]	37.6[a]	4.8[a]	0.0	0.0	0.59
17	*Linaria vulgaris* Mill.	66.8[a]	52.6[a]	39.3[a]	20.6[a]	11.4[a]	2.4	0.0	0.59
18	*Onopordum acanthium* L.	70.8[a]	60.3[a]	45.2[a]	28.4[a]	11.8[a]	0.7	0.0	0.56
19	*Plantago lanceolata* L.	78.2[a]	61.8[a]	50.1[a]	30.6[a]	15.5[a]	4.2	2.6	0.52
20	*Plantago major* L.	84.8[b]	63.6[a]	35.8[a]	20.6[a]	8.9[a]	2.6	0.0	0.62
21	*Rumex acetosella* L.	83.4[b]	77.5[a]	63.9[a]	42.8[a]	13.8[a]	2.0	1.2	0.47
22	*Rumex confertus* Willdenow	90.8[d]	83.9[a]	80.4[b]	45.8[a]	10.9[a]	1.8	0.0	0.42
23	*Sonchus arvensis* L.	83.6[b]	71.3[a]	60.4[a]	21.3[a]	8.6[a]	0.0	0.0	0.52
24	*Taraxacum officinale* Weber	90.4[c]	86.5[b]	79.6[b]	34.2[a]	21.3[a]	6.8	3.6	0.36
Tukey multiple comparisons of means 95% family-wise confidence level (the interval of a minimum level of allowable difference for p_{adj})		0.58–0.69	0.68–0.95	0.80–1.07	0.89–1.22	0.93–1.48	–	–	–

Significance levels to control (p): a – 0.1%; b – 1%; c – 5%;d – no significant difference.
*APG is the allelopathic potential on oilseed radish germination calculated for weed extracts concentrations of 1–4% with the same classes of allelopathic potential by Smith (2013).

In our opinion, the difference in the allelopathic impact on seed germination for the two variants is a measure of the importance of soil conditions for the manifestation of herbal competition of this species with the oilseed radish, which is confirmed in research by Meiners *et al.* (2017) and Kuht *et al.* (2016). We consider the fact that in its cycle of development, the critical period for weed control (CPWC (Knežević, Datta, 2015)) is typical for the period from 5–7 to 12–15 days of vegetation (Tsytsiura, 2020), which determines a specific competition of this species with other plant species (Lawley *et al.*, 2012). The presented averaged data show a general decrease in allelopathic effect on oilseed radish germination exactly when grown on the soil substrate by 0.2–2.0% depending on the extract concentration. The maximum difference is noted when comparing two germination variants in the concentration range of 0.25–2%, and the minimum 1 in the range of 8–16%. Moreover, the value of such reduction is species-specific. Therefore, for the species *Agropyron repens* (L.) Gould 1.1–3.5% and the species *Cyclachaena xanthiifolia* Nuttall 1.0–1.8%. This nature of the allelopathic effect has also been noted in the research of several scientists (Fujii *et al.*, 2004; Sturm *et al.*, 2016, 2018; Prinsloo, Plooy, 2018). In these researches, it is explained by the absorption and adsorption of several substances extracted into the solution during the extraction process. This confirms the statement that the allelopathic potential of a particular weed species is determined both by its stage phenological development and by the edaphic conditions of its growth and development, which determine both the vegetation intensity of the species, its vitality index and the degree of influence of its root excretions, given the favourable soil fertility conditions for the species itself. Thus, the use of two variants of seed germination provided the formation of similar features of seed germination in the dynamics of increasing the concentration of the extract while weakening the direct action of allelopathic substances of solutions due to the buffering features of the soil absorption complex in the "soil bioassay" variant (Table 4).

This conclusion is confirmed by the presented grouping. According to it some species of weeds belonged to different grouping intervals comparing both variants of germination. For *Linaria vulgaris* Mill APG interval is 0.61–0.65 for "Petri plate bioassays" and 0.56–0.60 for "soil bioassays", and for *Carduus acanthoid* L it is 0.41–0.45 and 0.31–0.35, respectively. The majority of species with the highest prevalence in the agrocenosis of oilseed radish by the criterion of frequency (F) belonged to the groups with APG> 0.50 for both germination variants.

Representatives of the families Asteraceae, Poaceae and Convolvulaceae played a dominant role in the intensity of allelopathic effects on oilseed radish. Representatives of these families had a high allelopathic activity to cruciferous and other species of agricultural plants.

The data obtained is also confirmed by the level of allelopathic effect on other cultivated plants from several weed species under study, including the representatives of the Convolvulaceae (COVF) family in the studies of Marinov-Serafimov *et al.* (2015), Dadkhah and Rassam (2016); Poaceae (1GRAF) family species in the studies of Einhellig *et al.* (1982), Awan *et al.* (2012), de Bertoldi *et al.* (2012), Anwar *et al.* (2019), Fragasso *et al.* (2013), Golubinova and Ilieva (2014); Asteraceae (1COMF) family species in the studies of Stevens (1986), Izzet *et al.* (2004), Awan *et al.* (2012), Możdżeń *et al.* (2018), Marinov-Serafimov *et al.* (2015, 2019); Polygonaceae (1POLF) family species in the studies of Anwar *et al.* (2013). According to the research results of the above-mentioned authors, the highest level of allelopathic potential was noted for the Asteraceae family representatives, and among the parasitic representatives of the Convolvulaceae family, in particular the *Cuscuta* (1CVCG) genus (Marinov-Serafimov *et al.*, 2017).

Table 4. Effect of weed extracts on seed germination of oilseed radish (BBCH 01–05*) are grouped according to their allelopathic potential (APG)

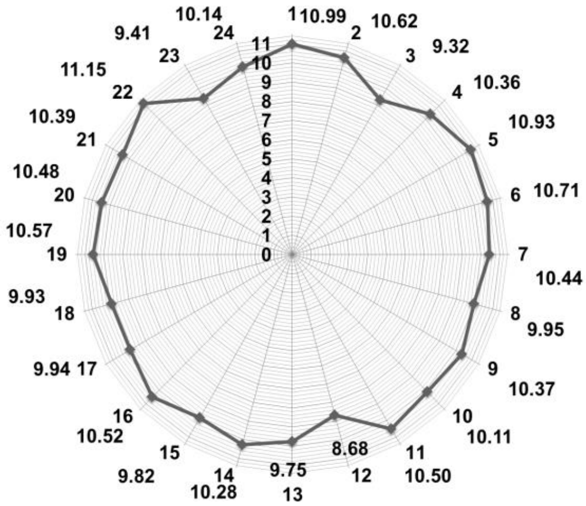
APG interval	Weed species, which belong to the interval group	
	Petri plate bioassays	soil bioassays
0.30–0.35	–	*Carduus acanthoides* L.., *Achillea millefolium* L.
0.36–0.40	*Achillea millefolium* L.	*Taraxacum officinale* Weber, *Cynodon dactylon* (L.) Pers.
0.41–0.45	*Carduus acanthoides* L., *Taraxacum officinale* Weber	*Artemisia vulgaris* L., *Rumex confertus* Willdenow, *Arctium lappa* L.
0.46–0.50	*Artemisia vulgaris* L., *Cynodon dactylon* (L.) Pers., *Rumex confertus* Willdenow, *Arctium lappa* L., *Rumex acetosella* L., *Echium vulgare* L.	*Artemisia absinthium* L., *Rumex acetosella* L., *Echium vulgare* L.
0.51–0.55	*Artemisia absinthium* L., *Cichorium intybus* L., *Plantago lanceolata* L.	*Cirsium arvense* (L.) Scopoli, *Sonchus arvensis* L., *Cichorium intybus* L., *Cyclachaena xanthiifolia* Nuttall, *Plantago lanceolata* L.
0.56–0.60	*Agropyron repens* L.) Gould, *Sonchus arvensis* L., *Equisetum arvense* L., *Cyclachaena xanthiifolia* Nuttall, *Onopordum acanthium* L.	*Agropyron repens* L.) Gould, *Convolvulus arvensis* L., *Linaria vulgaris* Mill., *Equisetum arvense* L., *Onopordum acanthium* L.
0.61–0.65	*Cirsium arvense* (L.) Scopoli, *Convolvulus arvensis* L., *Linaria vulgaris* Mill., *Plantago major* L.	*Plantago major L. Acroptilon repens* L.) de Candolle
0.66–0.70	*Acroptilon repens* L.) de Candolle, *Cuscuta campestris* Yuncker	*Cuscuta campestris* Yuncker

*Growth periodization by BBCH (Test guidelines…, 2017).

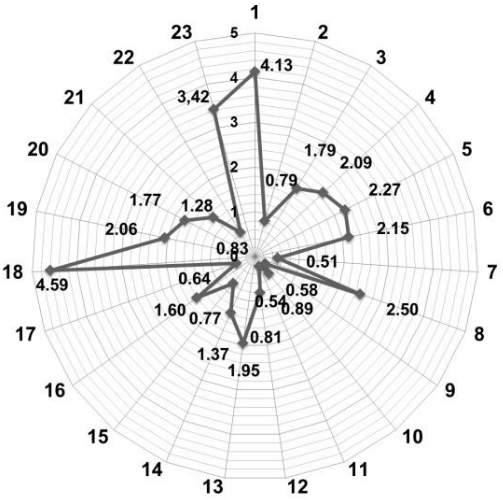
The very nature of the germination dynamics had a heterogeneous nature and species specificity from a slow-down nature to nature with leap-scopic decline, which points in favour of the biochemical causes (Reigosa *et al.*, 2006; Florence *et al.*, 2019). For a more detailed assessment of the nature of this dynamics, two indicators of the speed of germination (S) and the coefficient of the velocity of germination (CV_i) were used for the soil-free germination variant, which, as we found, is more biologically aggressive and needs to be evaluated typologically for the nature of similarity formation on an allelopathic background. These indicators are rarely applied to such research systems, but are very informative (Nasr, Mansour, 2005), as they demonstrate both the overall germination intensity and its dynamic nature for each additional day of the germination period.

The rate of seed germination (S) details the process of germinated seeds formation daily and determines the specific species" nature impact on this process considering the characteristics of the extract chemical structure. According to this indicator (Fig. 1), the researched weed species can be divided into several classification groups within each variant of the extract concentration. Thus, the specific effect of the extracts provides 10–11, 9–10 and 8–9 germinated seeds per germination day in comparison with the control variant of 10.99 germinated seeds per day in the 1.0% variant. This rate was 11.15 germinated seeds per day for *Rumex confertus* Willdenow; it was higher than the control variant; the minimum rate was 8.68 germinated seeds per day for the species *Cuscuta campestris* Yuncker. The indicator distribution by the weeds researched species changes significantly in the variant of 4.0% extract concentration and especially in the variant of 8.0%. Thus, the range of the indicator is 5.26–10.15 in the variant of 4.0% extract concentration.

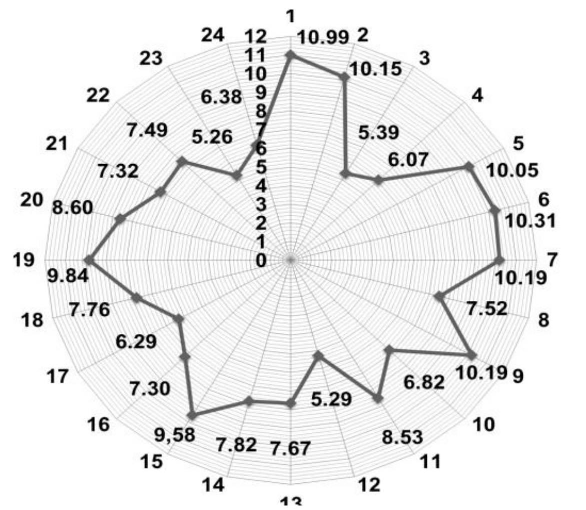
The value of this indicator decreased for species with a low presence in the cenosis of oilseed radish (*Arctium lappa* L.; *Artemisia absinthium* L.; *Artemisia vulgaris* L., *Cichorium intybus* L., *Echium vulgare* L., *Plantago lanceolata* L.) by 4.5–9.8% and was 9.58–10.31 germinated seeds per day compared to the concentration of 1.0%. The velocity interval was significantly lower and was 5.26–6.82 for the *Acroptilon repens* (L.) de Candolle, *Agropyron repens* (L.) Gould, *Cirsium arvense* (L.) Scopoli, *Sonchus arvensis* L. species with the highest precence by the frequency criterion F (Table 1) in the variant of the extract concentration of 4.0%. It should be noted that the rate of speed germination (S) in the variant of concentration of 8.0% also had certain features in the 8.0% variant concentration. Thus, the decrease was significantly higher for species with minimal presence with the same criterion of frequency (F), than for species that dominate in the agrocenosis of oilseed radish in the research area. For example, such species as *Carduus acanthoides* L. (S = 0.51), *Cichorium intybus* L. (S = 0.58), *Onopordon acanthium* L. (S = 0.64).



Weed extracts at 1%



Weed extracts at 8%



Weed extracts at 4%

Figure 1. The speed of seed germination (S) of oilseed radish growing under weed extracts at 1%, 4% and 8%. The Y-axis is scaled to indicate the number of oil radish seeds germinated per day when exposed to weed extracts.
1 – Control (Distilled water); 2 – *Achillea millefolium* L.; 3 – *Acroptilon repens* (L.) de Candolle; 4 – *Agropyron repens* (L.) Gould; 5 – *Arctium lappa* L.; 6 – *Artemisia absinthium* L.; 7 – *Artemisia vulgaris* L.; 8 – *Carduus acanthoides* L.; 9 – *Cichorium intybus* L.; 10 – *Cirsium arvense* (L.) Scopoli; 11 – *Convolvulus arvensis* L.; 12 – *Cuscuta campestris* Yuncker; 13 – *Cyclachaena xanthiifolia* Nuttall; 14 – *Cynodon dactylon* (L.) Pers.; 15 – *Echium vulgare* L.; 16 – *Equisetum arvense* L.; 17 – *Linaria vulgaris* Mill.; 18 – *Onopordon acanthium* L.; 19 – *Plantago lanceolata* L.; 20 – *Plantago major* L.; 21 – *Rumex acetosella* L.; 22 – *Rumex confertus* Willdenow; 23 – *Sonchus arvensis* L.; 24 – *Taraxacum officinale* Weber. (For the variant with an extract concentration of 8.0%, the control variant similar to the concentration of 1 and 4% was not shown on the graph while maintaining the same numbering of weed species as for the concentration of 1 and 4%).

Thus, speed of germination indicator allows for categorizing the extracts of the perennial weed into three groups: (i) 9–11 seeds day^{-1} where seed germination was completed after 3–5 days. Typical weed species in this group are *Convolvulus arvensis* L., *Artemisia vulgaris* L., *Artemisia absinthium* L., *Arctium lappa* L. and *Achillea millefolium* L.; (ii) 7–9 seeds day^{-1} at which germination of oilseed radish finished in 5 to 7 days. Typical weed species in this group are *Equisetum arvense* L., *Linaria vulgaris* Mill., *Cuscuta campestris* Yuncker; (iii) 5–7 seeds day^{-1} where full germination needed 5 to 9 days.

This group includes *Acroptilon repens* (L.) de Candolle, *Agropyron repens* (L.) Gould, *Sonchus arvensis* L., *Taraxacum officinale* Weber. This last group was characterized by the presence of "dormance seeds" which are swollen seeds with evident signs of germination initiation.

Weeds dominating the oilseed radish agrophytocoenosises in our research fields belong to both the third and the second groups mentioned. This finding suggests that the dominance of these weeds in oilseed radish fields is due, at least in part, to their allelopathic effects. This aspect is mentioned in some research (Cheng, Cheng, 2015; Arroyo *et al.*, 2018; Carvalho *et al.*, 2019).

Thus, the rate of germination rate details the gradations of allelopathic sensitivity of the species in the test-object system, *i.e.*, weeds in the early stages of germination, and allows identifying of certain typological groups of effects. It is confirmed by the Coefficient of velocity (CVi), which allowed us to assess the formation of germinated seeds of oilseed radish for each day of observation. The allelopathic effect of different weed species on radish seed germination shifts the germination pattern under appropriate standard laboratory germination conditions. Under these conditions, the germination of oilseed radish seeds is observed 6–7 days after the start of germination and some seeds had signs of germination in 3–5 days (Seeds quality ..., 2003). However, extracts of different species change the dynamics of germination. The range of CVi values by the standard deviation is significantly higher than for the treatment variant with extracts of 1.0% concentration in the case of 4.0% concentration variant in the interval from 3rd (CV3) to the 9th day (CV9) of germination (Fig. 2).

The maximum range interval for the extract concentration variant was observed on the seventh (CV7) and eighth (CV8) days of germination, and the minimum was observed on the ninth (CV9) with a steady increase in variation for the total population researched from the first to the eighth day of germination. The maximum range of values was observed mosaically on the 4th, 7th and 9th day of germination for the 1.0% concentration variant. It confirms our conclusions about the inhibition of physiological processes of germinated seeds formation with a shift of stages in 7–9 days for oilseed radish. Therefore, this effect should be expected for allelopathically aggressive species in comparison to the test object. On the other hand, the use of 1.0% extract provides a more even distribution of seed formation with signs of germination from the 3rd to 7th days. A percentage shift of normally germinated seeds from 4th to 9th days with a maximum value from 6th to 8th days of germination was observed for the variant of 4.0% concentration. That is, the effect of physiological depression and prolongation of stages of seed germination is observed.

The difference between our conclusions and similar research (Singh *et al.*, 2003; Uremis *et al.*, 2009; Toosi, Baki, 2011; Swanton *et al.*, 2015; Sturm *et al.*, 2018; Carvalho *et al.*, 2019; Ali *et al.*, 2019; Schandry, Becker, 2020) is to identify the processes of seed germination displacement beyond the biologically typical date of the species, according to the standards for germination determining.

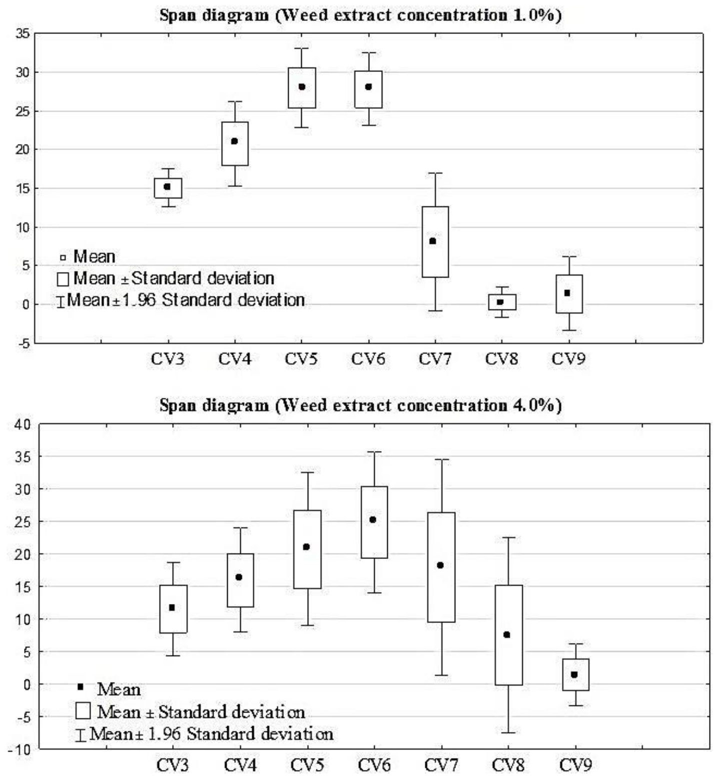


Figure 2. Span diagrams obtained for the means of the Coefficient of velocity of germination (CV_i) calculated from the third (CV3) to the nineth day (CV9) of oilseed radish germination.

According to the classical scheme, such seeds should be classified as seeds that have not germinated. The studied features require some revision using a wider interval than accepted by standard methods for estimating the value of seed germination considering oilseed radish allelopathic analysis at the stage of seed germination. Visually indicated features within the researched weed species are presented in Figure 3. Thus, most of the presented weed species provided a general decrease in the percentage of germinated seeds starting from the third day of germination with the increasing difference to 5th and 6th days for the variant of 1.0% extract concentration. The process of inhibiting germination by shifting the maximum proportion of germinated seeds on the 7th day of germination under the action of extracts for weed species such as *Acroptilon repens* (L.) de Candolle, *Cirsium arvense* (L.) Scopoli, *Plantago major* L. *Cyclachaena xanthiifolia* Nuttall was observed. It should also be noted that a germinated seed was observed on the 9th day of germination, it was not observed on the 8th day.

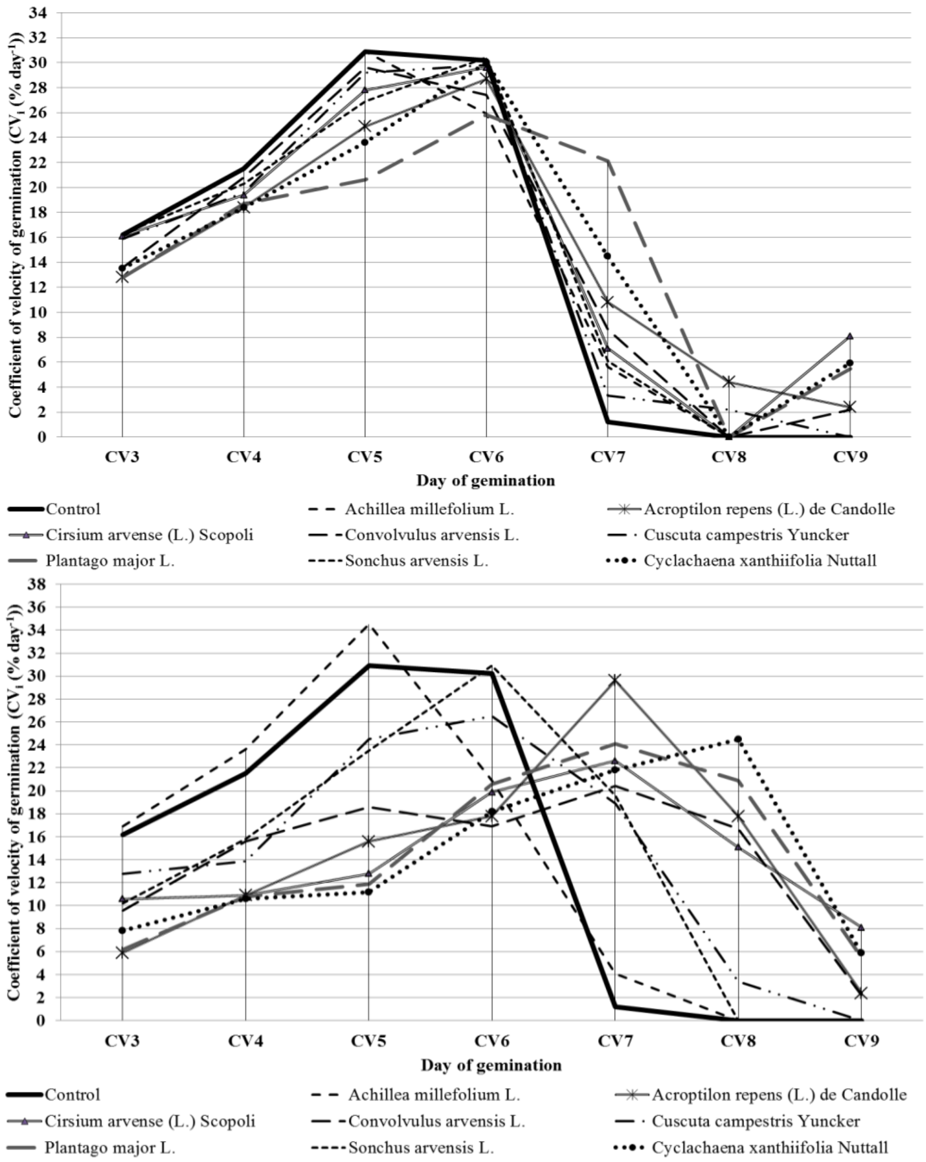


Figure 3. Coefficient of the velocity of germination (CVi (%)) calculated for oilseed radish germination exposed to distilled water (control) and some weed extracts at the concentration of 1% (upper position) and 4% (down position), from day 3rd (CV3) to day 9th (CV9). The units in the Y-axis indicate the % of germinated seeds on the ith day of germination.

The dynamic formation of the indicator had significant differences and species specificity at the variant of 4.0% extract concentration. Thus, a 4.0% concentration level is a threshold for oilseed radish (Melander *et al.*, 2016). The maximum CV index was observed on the 5th and 6th day of oil radish seeds germination of (parity at 30–31%) in the control variant. The peak values were observed in *Achillea millefolium* L. on the 5th day, in *Sonchus arvensis* L. on the 6th day, in *Acroptilon repens* (L.) de Candolle and *Convolvulus arvensis* L. on the 7th day, in *Cyclachaena xanthiifolia* Nuttall on the 8th day under the action of different species extracts. The maximum values of CV_i are achievable for oilseed radish on 6–8th days for species with higher allelopathic potential according to APG (Table 2), and on 4th–6th days of germination for species with significantly lower APG values. It should be noted that in both 1.0% and 4.0% extracted concentrations the seeds are swollen, lively, but not germinated according to the classical morphological parameters with the initial signs of germination after the 9th day.

Thus, the formation of germinated seeds in the extracts of certain species of weeds was observed (*Cuscuta campestris* Yuncker, *Equisetum arvense* L., *Cirsium arvense* (L.) Scopoli, *Acroptilon repens* (L.) de Candolle, *Carduus acanthoides* L.) on 11–12th days of germination under optimal germination conditions. The processes potential under the action of extracts of certain weed species is indicated in the studies of Marinov-Serafimov *et al.* (2017), Novak *et al.* (2018), and Khan *et al.* (2019).

Our research has confirmed this possibility and provides grounds for recommendations for changes in some approaches to the research of allelopathic effects and allelopathic sensitivity of biological test species at the stage of seed germination.

Conclusion

Oilseed radish was sensitive to water extracts of 23 perennial weed species tested in the range of concentrations of 0.25–16.0% (w/v).

The range growth of weed species allelopathic potential on their impact on seed germination according to APG averaged for two variants of germination was as follows: *Cuscuta campestris* Yuncker (APG (average for germination variants) 0.68) > *Acroptilon repens* (L.) de Candolle (0.66) > *Plantago major* L. (0.63) > *Linaria vulgaris* Mill. (0.61) > *Equisetum arvense* L. (0.60) > *Cirsium arvense* (L.) Scopoli, *Convolvulus arvensis* L. (0.59) > *Agropyron repens* (L.) Gould (0.58) > *Onopordum acanthium* L. (0.57) > *Cyclachaena xanthiifolia* Nuttall (0.55) > *Sonchus arvensis* L., *Cichorium intybus* L., *Plantago lanceolata* L. (0.54) > *Artemisia absinthium* L. (0.51) > *Echium vulgare* L., *Rumex acetosella* L. (0.48) > *Artemisia vulgaris* L. (0.47) > *Arctium lappa* L. (0.46) > *Cynodon dactylon* (L.) Pers., *Rumex confertus* Willdenow (0.44) > *Carduus acanthoides* L., *Taraxacum officinale* Weber (0.39) > *Achillea millefolium* L. (0.36).

It has been established that "speed of germination" and "coefficient of velocity of germination" can be used as effective indicators for assessing the allelopathic sensitivity of test objects. Thus, they were respectively 5–7 germinated seeds per day for the percentage of germinated seeds for 7–9 days over 30% of the total number laid for germination, and for species with weak allelopathic activity, respectively, 10–11 germinated seeds per day of germination and the percentage of germinated seeds per 7–9 days more than 4–15% of the total in the case of oilseed radish in allelopathically adhesive species at an extract concentration of 4.0%.

Taking into account the classification of allelopathic potential (Smith, 2013) with 47.8% of the researched species belonging to the Non-allelopathic (NA) class and the absence of weeds belonging to the class Highly allelopathic (HA) for the test object, radish oilseed should be considered as an effective candidate for its application in the system of weeds biological control of sidereal and mediator application in traditional rotational schemes of cultivation of major crops of the non-cruciferous group.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

YHT – drafting of the manuscript; analysis, interpretation and acquisition of data; study conception and design; critical revision and approval of the final manuscript.

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