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Original Paper

Allelopathic Effects of Annual Weeds on Germination and Seedling Growth of Oilseed Radish (*Raphanus sativus* L. var. *oleiformis* Pers.)

Yaroslav Tsytsiura[1], Diego Sampietro[2]
[1]*Vinnytsia National Agrarian University, Vinnytsia, Ukraine*
[2]*Universidad Nacional de Tucumán, Facultad de Bioquímica Química y Farmacia, Argentina*

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The allelopathic effects of 54 weed species were studied on oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) in Petri dish and soil bioassays. Weed extracts were prepared at concentrations of 0.25,0.5,1.0, 2.0, 4.0, 8.0 and 16.0% and assayed on seed germination and seedling growth. They showed a species-specific effect when tested in the range of concentrations of 1.0–4.0%. Seed germination was less inhibited in soil than in Petri dish assays. Indexes of allelopathic potential (AP) were separately calculated for germination (APG) and seedling growth (APRG for roots and APSG for shoots). They were in the range of 0.27–0.72 and 0.16–0.70, respectively. The weeds were classified according to their APSG and APRG indexes, and the percentage of appearance frequency (F) in oilseed radish fields, from more to less harmful, as: *Amaranthus retroflexus* > *Echinochloa crus-galli* (L.) P. Beauv > *Setaria glauca* L. > *Chenopodium album* L. > *Brassica napus* L. > *Galinsoga parviflora* Cavanilles > *Sinapis alba* L. > *Tripleurospermum maritimum* (L.) Koch > *Raphanus sativus* L. var. *oleiformis* Pers. > *Polygonum lapathifolium* (L.) Delarbre > *Setaria viridis* (L.) Palisot de Beauvois > *Barbarea vulgaris* Brown > *Brassica campestris* (L.) Janchen > *Lactuca serriola* L. > *Thlaspi arvense* L. > *Senecio vernalis* (Waldstein & Kitaibel) Alexander > *Lepidium draba* L.

Keywords: allelopathic potential, annual weeds, oilseed radish, seeds germination, seedling growth

1 Introduction

Weeds reduce the crop yields depending on the extent of infestation. Weeds are a detrimental threat to global crop production in both developing and developed countries. Overall, among the biotic factors causing crop losses, weeds contribute to the highest potential yield loss to crops, followed by animal pests (insects, mites, nematodes, birds, rodents, etc.) and pathogens (fungi, viruses, bacteria, etc. Annual crop losses and cost of weeds have been estimated to be at AUD 3.3 billion in Australia and USD 33 billion in the United States (Chauhan, 2020; Wong et al., 2022). On average, & Mauromicale (2020) calculated a potential loss of 34% of crop production caused by weed pressure, followed by –18% from animal pests and – 16% from pathogens. Furthermore, he estimated, as follows, the potential losses of six major herbaceous field crops: wheat – 23%, rice –37%, maize –40%, potato – 30%, soybean – 37% and cotton – 36%. By generalization Scavo and Mauromicale (2020) the annual global economic loss caused by weeds was more than 100 billion US dollars. For this reason, and considering also that weeds are a dynamic threat, weed control has always been placed in the center of the agricultural activity by farmers since ancient times.

Changes in the technological and edaphic vectors of agricultural production, such as a reduction in species diversity of crop rotations (Chauhan, 2020), a decrease in the effectiveness of chemical control agents due to the emergence of resistance to herbicide active ingredients (Gaines et al., 2020), a decrease in soil fertility potential and their consistent degradation, the general increase in environmental stress due to global climate change (Scavo & Mauromicale, 2020) – on the one hand, form additional advantages of different weed species in comparison to crop species, and on the other hand, lead to the search for alternative tactics of weed control in agrocenoses on a biological and species-population basis (Alagbo et al., 2022).

***Corresponding Author:** Yaroslav Tsytsiura, Vinnytsia National Agrarian University, Faculty of Agronomy and Forestry, 21008, Soniachna street, 3, Vinnytsia, Ukraine, yaroslavtsytsyura@ukr.net
https://orcid.org/0000-0002-9167-833X https://orcid.org/0000-0003-2956-74848

The monocropping exerts selection pressure on weed populations, where some species become dominant and hard to control. It has led to the intensive use of herbicides. Global warming also had the same effect, because several weed species are more competitive than crops under the new environmental conditions (Zimdahl, 2018). Hence, there is a need to find new strategies for weed control. Allelopathy has been currently addressed as an ecofriendly tool for weed management (Scavo et al., 2018). Its popularity is growing mainly in organic farming and sustainable agriculture. Weed management based on allelopathy may increase the sustainability of agroecosystems (Khamare et al., 2022). Allelopathic crops can release allelochemicals as root exudates (Scavo & Mauromicale, 2020; Bolouri et al., 2022), or from their decomposing residues (Scavo et al., 2020). Another approach is the herbicidal use of plant extracts to control weed species. Plant extracts can be applied alone or in combinations with commercial herbicides or microbial compounds (Scavo et al., 2020; Ayilara et al., 2023).

Oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers. Brassicaceae family) is an annual oilseed crop (Figure 1). It is widely cultivated in USA, Canada, Europe, Ukraine and semi tropical countries. It is also used as cover crop, fodder and green manure in organic farming (Tsytsiura, 2020). Oilseed radish as one of the representatives of the radish genus contain phenolics and glucosinolates allelochemicals that contributes to its allelopathic activity on weeds (Manivannan et al., 2019; Saman et al., 2020). Allelopathic effects of weeds on oilseed radish as well as its allopathic sensitivity are yet unknown.

It is noted that the allopathic potential of a crop can be divided into two main components (Abbas et al., 2021). The first of them is the direct allopathic effect, which implies the direct allopathic potential of a given species to other species that dominate or may dominate the cenosis depending on soil and climatic conditions and species diversity of the territory (Khamare et al., 2022). The second is considered as the allopathic sensitivity of the species itself in relation to the allopathic and vitalistic reactions of other species, which determines the level of their dominance and structure in agrophytocenoses (Motmainna et al., 2021; Choudhary et al., 2023). That is, it is the second component that will determine the potential level of weed infestation of a particular agrophytocenosis of the main crop in the species structure of the segetal component, which in turn will be determined by the allopathic response to a single species or polyphyllous weed infestation (Chaves et al., 2023).

In view of this, the main task was to determine the relationship between the level of weed infestation of oil radish agrophytocenosis with annual weeds and allopathic sensitivity to this group of weeds. This research aimed to evaluate the phytotoxic effects of extracts and rhizosphere soil from annual weed species on germination and seedlings growth of oilseed radish.

Figure 1 From the left – drawings of vegetative and reproductive plant parts of oilseed radish
1 – mature plant at flowering, 2 – seedling, 3 – mature plant at flowering, 4 – fruit (a siliqua), 5 – seed (an achene); from the right – oilseed radish at flowering in experimental field

2 Material and methods

2.1 Study Site

This research was performed in 2022 at Vinnytsia National Agrarian University (49° 11′ N, 28°22′ E), during the oilseed radish growing season of April-September (178 days). 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 annual weed species for research was conducted according to the criterion of frequency of appearance (F (Zimdahl, 2007)) of annual weeds from 2013 to 2018 in the oilseed radish fields located at the Vinnytsia National Agrarian University (Tsytsiura, 2020) for accepted marginal technological options for growing oilseed radish with clarification for the period 2019–2022 (Table 1).

The following methodology 2.2–2.8 fully corresponds to the one used in the study of allopathic sensitivity of oil radish to perennial weed species described in Tsytsiura (2022).

2.2 Extract preparation

The whole plants (aerial and underground parts) of 54 weed species selected according to the F values (Table 1) were collected at flowering stage in Fromour University 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 cutted 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 under the dark.

Extracts were prepared by immersion of each powdered sample in heated distilled water at 40 °C for 24 h (Inderjit & Dakshini, 1995; Fujii & Hiradate, 2007). Weights of 0.625 g, 1.25 g, 2.5 g, 5 g, 10 g, 20 g 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 each 2 hs. After heating, extracts were recovered by centrifugation at 4000 rpm and 30 °C for 30 s in a centrifuge Eppendorf model 5804R. Thereafter, the extracts were filtered through Whatman Filter paper # 1. The pH of the aqueous extracts was determined with an electronic pH meter Smart Sensor AS218.

2.3 Petri plate bioassays

They were performed in a complete randomized design with three factors which were (i) the weed species (54 species), (ii). the weed parts (root, stem, leaf and flower), and (iii) extracts concentration (0.25,0.5, 1, 2,4, 8 and 16%). A number of 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 in distilled water added instead of the water extracts. The Petri plates were kept in a BOD incubator at 25 °C and seed germination was recorded at the 6th day (Reigosa et al., 2006; Fujii & Hiradate, 2007). Speed of germination was recorded daily till the 6th day (Duke, 2015).

Table 1 Annual weed species involved in study (based on field monitoring during 2013–2020)

No.	Botanical Name	EPPO Code	Family	F
1	*Aethusa cynapium* L.	AETCY	Apiaceae	0.89*–0.56**
2	*Amaranthus blitoides* Watson	AMABL	Amaranthaceae	4.33–4.67
3	*Amaranthus retroflexus* L.	AMARE	Amaranthaceae	71.67–62.33
4	*Ambrosia artemisiifolia* L.	AMBEL	Asteraceae	0.23–0.15
5	*Avena fatua* L.	AVEFA	Poaceae	3.18–2.33
6	*Barbarea vulgaris* Brown	BARVU	Brassicaceae	22.67–6.67
7	*Berteroa incana* (L.) de Candolle	BEFIN	Brassicaceae	3.00–2.33
8	*Brassica campestris* (L.) Janchen	BRSRA	Brassicaceae	19.33–22.33
9	*Brassica napus* L.***	BRSNN	Brassicaceae	5.00–53.50
10	*Bromus secalinus* L.	BROSE	Poaceae	2.91–2.16
11	*Bunias orientalis* L.	BUNOR	Brassicaceae	3.08–1.56
12	*Capsella bursa-pastoris* L.	CAPBP	Brassicaceae	20.00–20.67

Continuation of Table 1

No.	Botanical name	EPPO Code	Family	F
13	*Centaurea cyanus* L.	CENCY	Asteraceae	10.67–11.00
14	*Chenopodium album* L.	CHEAL	Amaranthaceae	54.00–42.67
15	*Chondrilla juncea* L.	CHOJU	Asteraceae	8.67–2.67
16	*Crepis tectorum* L.	CVPTE	Asteraceae	2.75–1.18
17	*Consolida regalis* Gray	CNSRE	Ranunculaceae	1.09–0.86
18	*Daucus carota* L.	DAUCA	Apiaceae	7.33–3.67
19	*Descurainia sophia* (L.) Prantl	DESSO	Brassicaceae	0.59–0.44
20	*Digitaria ischaemum* (Schreber) Muhlenberg	DIGIS	Poaceae	4.29–3.56
21	*Echinochloa crus-galli* (L.) P.Beauv.	ECHCG	Poaceae	71.67–58.67
22	*Erigeron canadensis* L.	ERICA	Asteraceae	19.33–11.33
23	*Erodium cicutarium* (L.) L'Héritier	EROCI	Geraniaceae	2.57–1.69
24	*Eryngium campestre* L.	ERXCA	Apiaceae	0.71–0.52
25	*Fumaria officinalis* L.	FUMOF	Papaveraceae	3.18–2.56
26	*Galinsoga parviflora* Cavanilles	GASPA	Asteraceae	46.33–25.00
27	*Galium aparine* L.	GALAP	Rubiaceae	5.00–10.67
28	*Lactuca serriola* L.	LACSE	Asteraceae	21.67–10.67
29	*Lamium amplexicaule* L.	LAMAM	Lamiaceae	5.41–4.58
30	*Lamium purpureum* L.	LAMPU	Lamiaceae	5.00–6.00
31	*Lepidium campestre* (L.) Brown	LEPCA	Brassicaceae	10.27–8.96
32	*Lepidium draba* L.	CADDR	Brassicaceae	8.92–7.11
33	*Lepidium ruderale* L.	LEPRU	Brassicaceae	8.67–4.67
34	*Panicum capillare* L.	PANCA	Poaceae	3.08–2.18
35	*Papaver rhoeas* L.	PAPRH	Papaveraceae	5.11–3.52
36	*Poa annua* L.	POAAN	Poaceae	4.67–4.67
37	*Polygonum aviculare* L.	POLAV	Polygonaceae	4.67–3.00
38	*Polygonum convolvulus* (L.) Löve	PANCA	Polygonaceae	5.00–4.67
39	*Polygonum lapathifolium* (L.) Delarbre	POLLA	Polygonaceae	34.33–24.67
40	*Portulaca oleracea* L.	POROL	Portulacaceae	16.67–12.00
41	*Raphanus raphanistrum* L.	RAPRA	Brassicaceae	8.33–8.33
42	*Raphanus sativus* L. var. *oleiformis* Pers.***	RAPSO	Brassicaceae	3.50–40.70
43	*Senecio vernalis* (Waldstein & Kitaibel) Alexander	SENVE	Asteraceae	17.67–11.00
44	*Setaria glauca* L.	SETPU	Poaceae	62.33–56.00
45	*Setaria viridis* (L.) Palisot de Beauvois	SETVI	Poaceae	25.00–16.67
46	*Sinapis alba* L.***	SINAL	Brassicaceae	4.30–42.80
47	*Sinapis arvensis* L.	SINAR	Brassicaceae	8.67–8.00
48	*Sisymbrium loeselii* L.	SSYLO	Brassicaceae	2.18–1.20
49	*Solanum nigrum* L..	SOLNI	Solanaceae	0.62–0.45
50	*Spergula vulgaris* L.	SPRAR	Caryophyllaceae	5.00–4.67
51	*Stellaria media* (L.) Vill.	STEME	Caryophyllaceae	12.33–8.00
52	*Thlaspi arvense* L.	THLAR	Brassicaceae	7.67–21.0
53	*Tripleurospermum maritimum* (L.) Koch	MATMA	Asteraceae	16.33–42.67
54	*Veronica hederifolia* L.	VERHE	Plantaginaceae	12.00–4.67

* frequency (F) for 0.5 million seeds.ha^{-1} oilseed radish;** for 4.0 million seeds.ha^{-1}; *** cultivated species as weeds

2.4 Collection of rhizosphere soil

The rhizosphere soil of the 54 weed species was directly collected according to 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 1 mm mesh to remove coarse particles (root hair, etc). Then, the sieved soil samples were immediately used in bioassays (Fujii & Hiradate, 2007).

In all cases, the collected soil samples were classified as dark gray forest Luvic Greyic Phaeozem soils 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.

2.5 Soil bioassays

They also were performed in a complete randomized design with 3 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 distilled water. After 2 h, the seeds were sown in the center of each well. Seeds were placed at 2 cm depth. The 20 mL aqueous extracts of weeds.water^{-1} (Control treatment) per well was added on 1, 5 and 10 days after germination. One treatment had 10 wells and all treatments were replicated 5-times.

2.6 Measurements of seedling growth

Seedling growth was recorded after 18 days using the BBCH scale (Test Guidelines..., 2017). Seedlings were carefully removed from the wells. The roots were washed with running water to remove soil, and washed plants were dried with filter paper. After 10–15 min, root and stem length were measured and their fresh weights were recorded. For dry matter, the samples were dried in an oven at 105 °C for 8 h.

Intertool MT-3006 electronic caliper was used for linear measurements. Weight characteristics of plants were determined using electronic laboratory scales Certus CBA-300-0,005.

2.7 Gemination and growth indexes

They were calculated for oilseed radish in Petri plate and soil bioassays.

1. The speed of germination (*S*) was calculated by the following equation (1) (Duke, 2015; ISTA, 2020):

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

where: N_1, N_2, N_3… N_n... – the number of seeds germinated on day 1, 2, 3...*n*

2. Coefficient of velocity (CV_i) was recorded daily till the 9th day and was calculated by the adapted equation (2) (El-Gawad, 2014):

$$CV_i = \left(\frac{\sum Ni}{T} \right) \quad (2)$$

where: *N* – number of seeds germinated on day *i*; *T* – number of days from sowing

3. Percent inhibition (*IR*) was calculated according to the following equation (3) (Marinov-Serafimov et al., 2017):

$$IR = \frac{C - T}{C} \times 100 \quad (\%) \quad (3)$$

where: *C* – shoot or root length or biomass in control; *T* – shoot or root lengh or biomass

4. Allelopathic potential was calculated for seed germination (APG) and root and shoot growth (APRG and APSG, respectively). Allelopathic potential was determined by the equation (4) (Rueda-Ayala et al., 2015):

$$APG\,(APRG, PSG) = \frac{\left((IR_a + IR_b)/2\right)}{100} \quad (4)$$

where:, *IRa* and *IRb* – germination, or root or shoot growth inhibitions recorded at weed extract concentrations of 1% and 4%, respectively

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).

5. The seed germination (%) in determining the variance was calculated after preliminary arcsin-transformation following the equation (5):

$$Y = \arcsin\left(\sqrt{\frac{x\,\%}{100}} \right) \quad (5)$$

2.8 Statistical analysis

Basic statistical data analysis (including ANOVA) was done with Microsoft Office Excel 2010 (Microsoft Corp., Redmond, WA, USA) and Statistica 10 (Dell Software Company, TIBCO, USA). Figures were constructed with Microsoft Office Excel 2010 and Statistica 10. Tukey multiple comparisons of means 95% family-wise confidence level were performed with the R-statistica (v 4.2.1) (The R Foundation for Statistical Computing).

3 Results and discussion

Table 1 shows 54 weed species selected for extract preparation according to their appearance in the oilseed radish fields from 2013 to 2020 (Table 1). It indicated that, although weed composition was dominated by Brassicaceae (30%), Asteraceae (17%) and Poaceae species (15%), weed frequency (F) indicated that some Amaranthaceae (*Amaranthus retroflexus* and *Chenopodium album*) and Poaceae species (*Echinochloa crus-galli* and *Setaria glauca*) were the weeds most widely distributed each year in the fields. Table 1 includes some Brassicaceae crops (*Brassica napus*, *Sinapis alba* and *Raphanus sativus* L. var. *oleiformis*) originally cultivated in the lands currently used for oilseed radish which escaped cultivation and became weeds. The weed extracts were tested at maximum and minimum concentrations of 0.25 and 16.0% (p/v), respectively. Table 2 shows the pH values recorded at these concentrations together with the corresponding percentage of oilseed radish germination obtained in Petri dish and soil bioassays. The pH value of each weed extract decreased with the rise of its concentration. The increase varied among the weed species in a range of 0.7–1.6. These results indicate that the plant materials differed each other in their buffering capacity which could be mantained when weed extracts were tested in both Petri dish and soil bioassays. Table 2 suggests that variations in the pH from acidic to less acidic values reduced the inhibition of oilseed radish germination. Most weed extracts tested at concentration of 16.0% showed strongly acidic pH values (pH 4.5–5.5) related with a strong suppression of seed germination. It is the case of extracts from *Thlaspi arvense*, *Papaver rhoeas*, *Raphanus raphanistrum*, *Tripleurospermum maritimum*, *Chenopodium album*, *Brassica napus*, *Barbarea vulgaris*, *Sinapis arvensis*, *Arctium lappa*, *Eryngium campestre*, *Lepidium ruderale*, *Sinapis alba*, *Lepidium draba*, *Portulaca oleracea*, *Fumaria officinalis*, *Senecio vernalis*, *Amaranthus blitoides* and *Polygonum convolvulus*. Some weed extracts showed slightly acidic pH values (pH 6.1–5.5) at 0.25% (e. g. *Solanum nigrum*) which are into the soil pH ranges (5.5–6.5) required for optimum growth of oilseed radish (Ricardo et al., 2018) and were associated to the dissapearance or a drastical decrease of inhibition. Correlation analyses also support a pH dependance of oilseed radish germination. The influence of pH index of water extracts was confirmed by the nature of correlation dependence between its value at the water extract concentration of 0.25% of different plant species and indicators of oilseed radish seed germination (0.333 (p <0.05) for Petri dish bioassays and 0.407 (p <0.05) for soil bioassays). Nevertheless, it must be noted that extracts were not investigated in their osmotic potential values and allelochemical composition that usually have a strong inhibitory activity on seed germination and early seedling growth (Reigosa et al., 2006; Smith, 2013). Hence, further research is needed to elucidate the actual role of pH in the Petri dish and soil bioassays.

Table 2 and 3 also shows the indexes of allelopathic potential calculated according to seed germination (APG) of oilseed radish exposed to weed extracts at 1 and 4%. The allelopathic potential indexes (APG, APSG or IAP) are a standarized measure of the inhibitory effect of the weed extracts on germination, seedling growth, or both, respectively, of a receptor plant where a higher value indicates a stronger inhibition (Far & Bagherzadeh, 2018). Hence, it expresses the species specific allelopathic impact of the weed extracts. The APG indexes were obtained in the range 0.26–0.75 and clustered in 0.04 intervals which defined 10 groups. The APG values allowed to separate weeds in species with moderate (APG < 0.5) and high allelopathic potential (APG > 0.50). The weeds with high allelopathic potential were ordered according to their AP indexes as follows: *Amaranthus retroflexus* (APG = 0.64–0.67) > *Raphanus raphanistrum* (APG = 0.63–0.67) > *Chenopodium album* (APG = 0.63–0.67) > *Papaver rhoeas* (APG = 0.61–0.68) > *Brassica campestris* (APG = 0.60–0.67) > *Sinapis arvensis* (APG = 0.62–0.64) > *Consolida regalis* (APG = 0.60–0.63) > *Amaranthus blitoides* (APG = 0.60–0.62) > *Fumaria officinalis* (APG = 0.60–0.62) > *Galinsoga parviflora* (APG = 0.57–0.62) > *Polygonum convolvulus* (APG = 0.58–0.60) > *Barbarea vulgaris* (APG = 0.56–0.59) >*Sisymbrium loeselii* (APG = 0.54–0.57) > *Lepidium draba* (APG = 0.54–0.57) > *Chondrilla juncea* (APG = 0.52–0.55) >*Echinochloa crus-galli* (APG = 0.47–0.57) > *Descurainia sophia* (APG = 0.49–0.53) >*Ambrosia artemisiifolia* (APG = 0.47–0.53) > *Setaria viridis* (APG = 0.48–0.52) > *Polygonum lapathifolium* (APG = 0.45–0.54).

Oilseed radish was very sensitive to the extracts of most weed species, with a strong inhibition in seed germination in both Petri dish and soil bioassays already at the concentration of 0.25%. The high allelopathic sensitivity of oilseed radish should have a negative impact in the formation of its own cenosis (Lawley et al., 2012; Tsytsiura, 2020b).

Many studies show that plant extracts generate allelopathic responses in the range of concentrations of 0.1–32% (Lorenzo et al., 2013), with a strong reduction in seed germination already observed at 0.5–1.5% (Choudhary et al., 2023). Early studies also noted that extracts from donor plants vary in their allelopathic effect according to their cultivation time and the proximity of weed species (Chaves et al., 2023). Weed allelopathy usually increases with long-term agricultural use where a narrow number of weed species, the most agressive ones, remains in the field (Abbas et al., 2021). The results

Table 2 Germination (%) and allelopathic potential on seed germination (APG) in Petri dish bioassays for oilseed radish seeds

Weeds aqueous extracts	$pH_{conc.}$		Concentration, w/v (%)							APG (for conc. 1–4%)
	0.25	16.0	0.25	0.5	1.0	2.0	4.0	8.0	16.0	
Control (distilled water)	7.0	7.0	92.3	92.7	92.8	93.5	91.4	92.6	93.4	–
Aethusa cynapium	5.8	5.1	66.3	54.7	41.6	29.5	18.3	1.7	0.0	0.56
Amaranthus blitoides	5.5	4.7	67.8	52.6	40.5	19.1	8.6	0.0	0.0	0.62
Amaranthus retroflexus	6.3	5.1	60.9	42.7	33.6	17.1	5.5	0.0	0.0	0.67
Ambrosia artemisiifolia	6.5	5.7	70.7	62.1	52.4	34.2	16.2	0.0	0.0	0.53
Avena fatua	6.5	5.6	83.2	67.8	54.5	34.5	18.3	3.1	1.8	0.51
Barbarea vulgaris	5.9	4.9	83.4	47.9	39.6	28.5	14.1	0.0	0.0	0.59
Berteroa incana	6.3	5.2	75.6	64.5	55.4	32.4	18.2	0.0	0.0	0.50
Brassica campestris	6.5	5.7	70.5	56.7	38.5	9.3	3.2	0.0	0.0	0.67
Brassica napus	5.6	4.7	65.9	58.1	47.8	32.4	11.4	0.0	0.0	0.57
Bromus secalinus	6.3	5.5	86.9	79.6	68.3	54.2	25.1	5.3	2.9	0.42
Bunias orientalis	6.2	5.4	82.6	75.9	61.3	41.4	16.5	2.4	0.0	0.49
Capsella bursa-pastoris	6.8	5.2	85.8	73.2	47.3	21.6	10.3	1.1	0.0	0.58
Centaurea cyanus	6.7	5.6	90.1	78.4	68.7	47.2	30.2	6.8	4.2	0.40
Chenopodium album	6.0	4.9	67.2	46.2	29.7	18.6	7.2	0.0	0.0	0.67
Chondrilla juncea	6.1	5.3	74.2	61.2	49.5	37.8	14.2	2.5	1.4	0.55
Crepis tectorum	6.3	5.3	85.2	70.8	63.2	38.3	18.6	2.3	1.1	0.47
Consolida regalis	6.3	5.2	84.1	60.9	32.5	21.4	11.3	3.9	1.8	0.63
Daucus carota	6.3	5.5	86.3	78.5	64.5	37.4	21.6	4.2	1.8	0.45
Descurainia sophia	6.5	5.2	86.9	74.2	59.6	29.2	11.2	2.2	0.0	0.53
Digitaria ischaemum	6.3	5.5	80.5	69.8	57.5	39.2	19.3	4.1	2.9	0.49
Echinochloa crus-galli	6.5	5.1	73.6	61.8	52.4	21.5	8.3	0.0	0.0	0.57
Erigeron canadensis	6.1	5.4	84.7	78.8	74.5	59.2	38.5	6.1	2.7	0.34
Erodium cicutarium	6.3	5.5	89.3	82.9	73.7	52.1	27.4	6.2	5.1	0.39
Eryngium campestre	5.5	4.5	90.8	85.2	74.4	36.6	11.5	1.9	0.0	0.46
Fumaria officinalis	5.9	4.8	74.5	59.6	41.4	27.5	8.4	1.4	0.0	0.62
Galinsoga parviflora	6.4	5.3	63.3	42.7	35.6	21.5	11.5	2.2	0.0	0.62
Galium aparine	6.3	5.1	71.8	62.5	55.5	11.5	6.5	0.0	0.0	0.58
Lactuca serriola	6.7	5.5	88.7	82.8	79.3	57.6	21.7	3.7	1.1	0.39
Lamium amplexicaule	6.1	5.2	87.2	74.5	58.7	42.7	21.5	6.7	3.1	0.47
Lamium purpureum	6.2	5.4	87.8	77.9	69.4	51.5	24.3	6.9	2.2	0.42
Lepidium campestre	6.1	5.2	92.0	90.2	84.2	67.4	32.2	3.3	3.4	0.32
Lepidium draba	5.7	4.9	68.7	59.3	47.2	31.4	12.5	0.0	0.0	0.57
Lepidium ruderale	5.8	4.7	90.2	86.2	78.6	39.1	12.4	0.0	0.0	0.44
Panicum capillare	6.4	5.3	86.8	78.9	69.2	47.8	26.2	7.1	3.9	0.41
Papaver rhoeas	6.0	4.7	69.7	57.3	29.6	14.4	6.1	0.0	0.0	0.68
Poa annua	6.3	5.5	90.8	82.3	79.7	58.6	34.3	8.9	5.4	0.33
Polygonum aviculare	6.6	5.7	91.4	82.6	69.5	48.4	14.1	5.3	1.6	0.47
Polygonum convolvulus	6.3	5.0	63.2	50.8	41.4	21.7	10.4	0.0	0.0	0.60
Polygonum lapathifolium	6.2	5.3	68.4	58.1	49.5	28.4	16.1	0.0	0.0	0.54
Portulaca oleracea	5.7	4.9	78.9	60.8	48.5	31.7	6.3	0.0	0.0	0.60

Continuation of Table 2

Weeds aqueous extracts	$pH_{conc.}$		Concentration, w/v (%)							APG (for conc. 1–4%)
	0.25	16.0	0.25	0.5	1.0	2.0	4.0	8.0	16.0	
Raphanus raphanistrum	6.0	4.8	67.4	51.2	38.7	21.4	3.6	0.0	0.0	0.67
Raphanus sat. var. *oleiformis*	6.1	5.5	67.2	45.9	34.8	9.5	2.4	0.0	0.0	0.72
Senecio vernalis	5.7	4.9	76.9	65.8	56.4	32.1	14.2	1.1	0.0	0.52
Setaria glauca	6.3	5.2	78.5	71.6	67.2	37.5	28.3	2.8	0.0	0.41
Setaria viridis	6.2	5.1	75.2	66.3	51.5	36.5	17.2	4.1	0.0	0.52
Sinapis alba	5.8	4.8	56.9	47.2	38.7	27.5	9.3	0.0	0.0	0.62
Sinapis arvensis	5.7	4.8	69.4	57.8	45.5	19.3	3.2	0.0	0.0	0.64
Sisymbrium loeselii	6.0	5.1	74.1	56.9	47.7	32.5	11.1	2.1	0.9	0.57
Solanum nigrum	6.2	5.5	81.4	68.9	50.7	31.7	12.4	3.9	1.1	0.55
Spergula vulgaris	6.2	5.3	86.9	80.7	71.8	48.4	22.5	7.3	4.2	0.42
Stellaria media	6.4	5.6	86.7	84.2	78.3	53.3	24.1	3.9	1.6	0.38
Thlaspi arvense	6.8	4.7	69.7	61.3	49.2	35.5	19.4	3.9	1.5	0.52
Tripleurospermum maritimum	5.9	4.8	78.3	50.8	41.9	24.2	8.4	0.0	0.0	0.61
Veronica hederifolia	6.4	5.6	86.3	70.5	62.5	46.4	27.8	8.1	3.8	0.43
Tukey's test 95% family-wise confidence level (interval min. level of allowable difference for p_{adj})	–	–	0.61–0.84	0.77–1.09	0.93–1.32	1.17–1.74	1.55–2.19	–	–	–

Table 3 Germination (%) and allelopathic potential on seed germination (APG) in Soil bioassay for oilseed radish seeds

Weeds aqueous extracts	Concentration, w/v (%)							APG (for conc. 1-4%)
	0.25	0.5	1.0	2.0	4.0	8.0	16.0	
Control (distilled water)	91.6	90.3	89.8	90.6	89.2	88.7	90.2	–
Aethusa cynapium	72.8	62.3	48.9	27.2	15.4	1.3	0.0	0.53
Amaranthus blitoides	68.4	54.7	39.6	18.7	9.2	0.0	0.0	0.60
Amaranthus retroflexus	63.2	44.8	35.6	19.6	6.9	0.0	0.0	0.64
Ambrosia artemisiifolia	76.9	68.9	56.3	42.5	19.6	0.8	0.0	0.47
Avena fatua	81.9	65.6	55.8	32.5	17.8	2.5	1.6	0.49
Barbarea vulgaris	85.1	53.6	40.8	32.3	15.6	0.0	0.0	0.56
Berteroa incana	78.1	66.7	57.8	33.9	21.3	0.0	0.0	0.46
Brassica campestris	74.8	60.3	42.6	12.6	7.8	0.0	0.0	0.60
Brassica napus	68.7	59.6	49.6	34.5	13.9	0.0	0.0	0.53
Bromus secalinus	84.5	78.4	66.8	53.2	23.6	4.8	2.6	0.41
Bunias orientalis	83.6	77.8	62.6	39.8	15.2	2.1	0.0	0.47
Capsella bursa-pastoris	89.3	78.9	58.7	30.2	16.8	1.9	0.9	0.48
Centaurea cyanus	90.8	81.3	70.4	49.2	33.5	7.9	5.7	0.35
Chenopodium album	69.1	48.4	32.3	20.8	9.1	0.0	0.0	0.63
Chondrilla juncea	78.7	60.3	50.8	35.9	15.2	2.3	1.7	0.52
Crepis tectorum	83.8	72.4	61.8	40.5	19.6	2.6	1.3	0.45
Consolida regalis	85.6	62.5	34.8	22.6	12.8	5.2	2.6	0.60
Daucus carota	82.8	76.5	69.6	42.3	25.6	5.6	2.7	0.39

Continuation of Table 3

Weeds aqueous extracts	Concentration, w/v (%)							APG (for conc. 1-4%)
	0.25	0.5	1.0	2.0	4.0	8.0	16.0	
Descurainia sophia	88.9	75.6	61.2	30.8	12.9	2.6	0.0	0.49
Digitaria ischaemum	78.9	70.4	58.6	40.8	18.6	3.8	2.7	0.47
Echinochloa crus-galli	78.9	65.8	56.9	29.2	13.8	0.0	0.0	0.47
Erigeron canadensis	87.2	81.4	77.9	62.3	41.6	6.9	3.5	0.28
Erodium cicutarium	87.5	80.6	69.8	53.8	29.6	6.7	4.8	0.37
Eryngium campestre	91.8	86.5	75.2	37.8	12.6	2.5	0.0	0.43
Fumaria officinalis	75.8	60.2	39.8	26.3	8.9	1.6	0.0	0.60
Galinsoga parviflora	65.9	46.2	40.5	23.5	13.8	3.4	0.0	0.57
Galium aparine	75.3	68.7	57.8	20.2	15.4	0.0	0.0	0.49
Lactuca serriola	90.9	84.1	80.5	60.2	22.6	4.5	1.9	0.35
Lamium amplexicaule	86.3	75.5	57.6	42.8	23.8	5.6	3.2	0.45
Lamium purpureum	89.2	78.7	71.2	50.8	21.3	5.5	1.8	0.40
Lepidium campestre	91.2	90.8	85.7	70.1	35.6	5.2	4.5	0.27
Lepidium draba	70.1	60.9	48.6	32.5	13.6	0.0	0.0	0.54
Lepidium ruderale	91,0	87.3	80.1	40.9	13.8	0.0	0.0	0.40
Panicum capillare	85.3	77.4	70.8	51.3	27.8	8.3	4.2	0.37
Papaver rhoeas	72.6	60.8	35.6	21.4	10.9	0.0	0.0	0.61
Poa annua	88.9	83.6	80.4	59.6	35.6	9.3	5.3	0.29
Polygonum aviculare	92.4	83.6	70.8	50.2	15.9	6.7	2.9	0.43
Polygonum convolvulus	64.5	52.6	43.2	20.3	9.8	0.0	0.0	0.58
Polygonum lapathifolium	72.6	60.3	55.8	32.4	20.9	0.0	0.0	0.45
Portulaca oleracea	79.3	61.8	50.2	33.6	7.8	0.0	0.0	0.57
Raphanus raphanistrum	70.8	53.6	40.8	23.6	5.1	0.0	0.0	0.63
Raphanus sativus var. *oleiformis*	70.3	48.9	39.6	11.4	5.2	0.0	0.0	0.68
Senecio vernalis	77.4	63.9	54.8	33.4	15.1	1.3	0.0	0.50
Setaria glauca	81.8	78.9	72.5	44.5	32.6	3.6	0.0	0.35
Setaria viridis	77.6	67.4	53.8	38.4	19.6	4.9	0.0	0.48
Sinapis alba	58.1	48.4	39.8	29.2	10.6	0.0	0.0	0.59
Sinapis arvensis	70.8	59.3	47.2	20.8	3.9	0.0	0.0	0.62
Sisymbrium loeselii	75.2	57.1	49.2	33.6	12.5	2.5	1.2	0.54
Solanum nigrum	83.2	67.1	49.8	32.8	12.9	3.3	1.5	0.54
Spergula vulgaris	88.5	82.4	72.3	49.6	24.5	7.7	4.3	0.38
Stellaria media	87.4	86.9	83.1	61.8	28.7	5.1	2.9	0.31
Thlaspi arvense	77.6	67.2	54.7	42.6	23.5	5.2	2.6	0.46
Tripleurospermum maritimum	80.4	52.8	43.6	29.3	11.5	0.0	0.0	0.57
Veronica hederifolia	87.4	72.8	63.5	45.8	25.6	7.4	3.6	0.42
Tukey's test 95% family-wise confidence level (interval min. level of allowable difference for p_{adj})	0.58–0.82	0.71–1.14	0.82–1.19	0.93–1.38	1.12–1.98	–	–	–

obtained in Petri dish and soil bioassays suggest that allelopathy is a major player in weed interference exerted on oilseed radish, given the fact that oilseed radish cultivation is limited in many regions with dominance of several of the weeds tested.

Weed extracts inhibited oilseed radish germination in Petri dish assays more than in soil bioassays. Inhibition was in average 0.2–2.0% higher in soil bioassays, specially in the range of concentrations of 0.25–2%. The maximum difference is noted when comparing two germination variants in the concentration range of 0.25–2%, and the minimum one in the range of 8–16%. The magnitude of the inhibition was species-specific. For example, inhibitions generated by extracts of *Capsella bursa-pastoris* and *Polygonum aviculare* were in the range 0.9–10.4% and 1.0–1.8%, respectively. This nature of allelopathic effect has also been noted in the researches of several scientists (Fujii et al., 2005; Reigosa et al., 2006; Marinov-Serafimov et al., 2019). In these researches it was explained by the absorption and adsorption of a number of substances extracted into the solution during the extraction process. In fact, 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 (such as vitality index, degree of influence of its root excretions, favorable soil fertility conditions). At the same time, this actualizes the importance of the ratios in the plant-weed system and the role of soil conditions for oil radish. Based on the research data, the abundance of annual weed species with a pronounced positive bioindication for improving soil conditions will be higher, as well as the allopathic pressure in the agrocenosis of oilseed radish. This is also confirmed by the statement that soil is a key factor involved in the allelopathic interactions among terrestrial plants (Macias et al., 2003; Marinov-Serafimov et al., 2019; Scavo et al., 2019). Allelochemicals likely were subjected to biotic (e. g. microbial degradation) and abiotic factors (e.g. sorption and desorption forces, spontaneous oxidation) which reduced their availability for the receptor plants (Fujii et al., 2005; Khamare et al., 2022).

On the other side the inhibition of oilseed radish in soil bioassays can be associated to the critical period for weed control (CPWC) of oilseed radish which ocurrs from 5 to 45 d after emergence (Tsytsiura, 2020a) and determines crop productivity when exposed to the competitive and allelopathic interferences of other plant species (Scavo et al., 2018). It is interesting to note that weed species showing dominance in the oilseed radish coenoses had a strong allelopathic effect in the concentration range of 1–4%. Other weeds that are less commonly found in the fields and occupy the lower tiers of oilseed radish agrocenoses (Tsytsiura, 2020a) exerted a strong allelopathic pressure at concentrations of 4–8% They include *Veronica hederifolia*, *Spergula vulgaris*, *Poa annua*, *Panicum capillare*, *Lepidium campestre*, *Erodium cicutarium*, *Erigeron canadensis*, *Digitaria ischaemum*, *Centaurea cyanus*, *Bromus secalinus* and *Avena fatua*. Some weed extracts tested at low concentrations (0.25–0.5%) had a neutral or hormetic effect on seed germination. It is the case of *Centaurea cyanus*, *Eryngium campestre*, *Lactuca serriola*, *Lepidium campestre*, *Lepidium ruderale* and *Polygonum aviculare*. The possibility of such a nature of formation of allopathic sensitivity depending on the allometric competitiveness of the weed by the nature of altitude dominance is indicated in a several publications (Rueda-Ayala et al., 2015; Marinov-Serafimov et al., 2017; Zimdahl, 2018; Saman & Kawa, 2020).

The APG values clearly indicated that the inhibitory effect of the weed extracts was species-specific (Smith, 2013). Two indexes, the speed germination (*S*) and the coefficient of velocity (CV_i), were calculated to understand intensity and dynamics of oilseed radish seed germination in the Petri plate bioassays (Możdżeń et al., 2018; Tsytsiura, 2022). The *S* expresses the rate of germination in terms of the total seeds germinated in a time interval while CV_i measures the rate and timespread of germination. The weed extracts tested at 4% in relation to the concentration at 0.25% produced strong fluctuations in the *S* values (Figure 2), with numbers ranging from 4.77 seeds.day^{-1} for *Amaranthus retroflexus* to 11.18 seeds.day^{-1} recorded for *Centaurea cyanus*. Speed of germination allows to categorize the weed extracts into three groups:

1. 9–11 seeds.day^{-1} where seed germination was completed after 3–5 days. Weed species included in this group are *Centaurea cyanus*, *Stellaria media*, *Berteroa incana*, *Barbarea vulgaris*, *Arctium lappa*, *Daucus carota*, *Erigeron canadensis*, *Eryngium campestre*, *Lepidium campestre* and *Aethusa cynapium*.
2. 7–9 seeds.day^{-1} at which germination of oilseed radish finished in 5 to 7 days.
   It compriss *Capsella bursa-pastoris*, *Raphanus raphanistrum*, *Sinapis alba*, *Portulaca oleracea*, *Amaranthus blitoides* and *Polygonum convolvulus*.
3. 4–7 seeds.day^{-1} where full germination needed 5 to 9 days. This group includes as typical representatives to *Galium aparine*, *Ambrosia artemisiifolia*, *Echinochloa crus-galli*, *Polygonum lapathifolium*, *Brassica campestris*, *Amaranthus retroflexus* and *Chenopodium album*. It was characterized by the presence of 'sleeping seeds' which are swollen seeds with evident signs of germination.

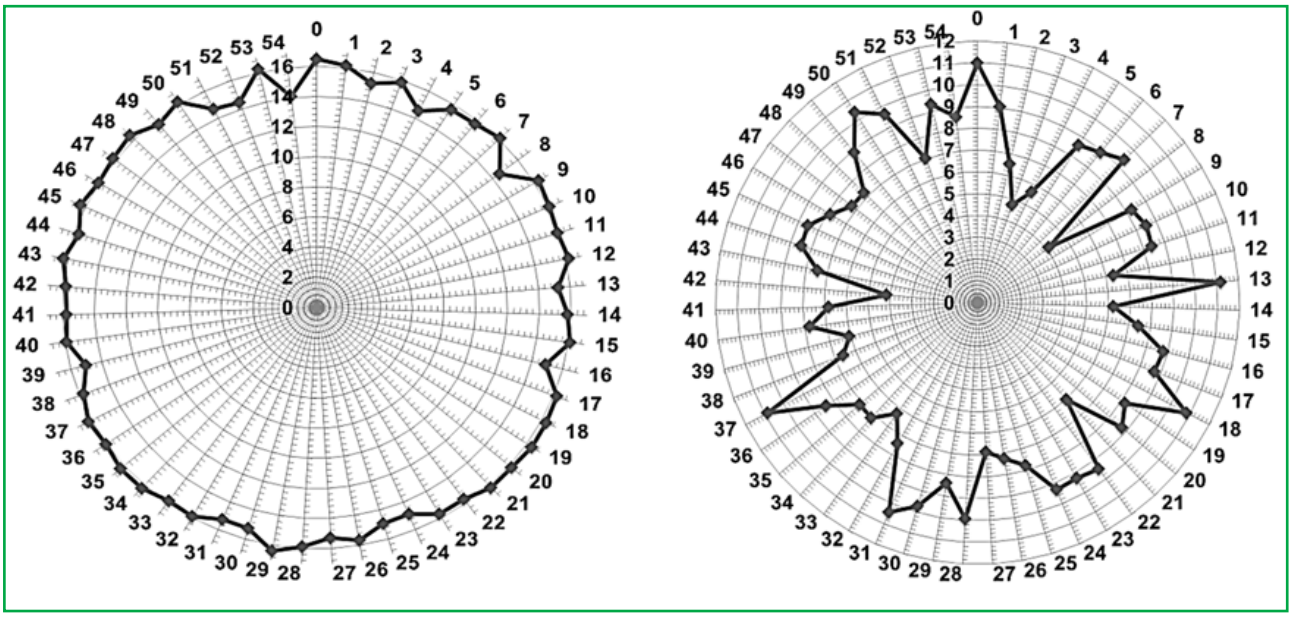

Figure 2 Speed of seed germination (seeds germinated.day^{-1}) recorded for oilseed radish exposed to the weeds extracts tested at the concentration of 0.25% (on the left) and 4% (on the right). Outer circle numbers indicate *Y*-axys devoted to annual weeds

0 – Control (Distilled water), 1 – *Aethusa cynapium*, 2 – *Amaranthus blitoides*, 3 – *Amaranthus retroflexus*, 4 – *Ambrosia artemisiifolia*, 5 – *Avena fatua*, 6 – *Barbarea vulgaris*, 7 – *Berteroa incana*, 8 – *Brassica campestris*, 9 – *Brassica napus*, 10 – *Bromus secalinus*, 11 – *Bunias orientalis*, 12 – *Capsella bursa-pastoris*, 13 – *Centaurea cyanus*, 14 – *Chenopodium album*, 15 – *Chondrilla juncea*, 16 – *Crepis tectorum*, 17 – *Consolida regalis*, 18 – *Daucus carota*, 19 – *Descurainia sophia*, 20 – *Digitaria ischaemum*, 21 – *Echinochloa crus-galli*, 22 – *Erigeron canadensis*, 23 – *Erodium cicutarium*, 24 – *Eryngium campestre*, 25 – *Fumaria officinalis*, 26 – *Galinsoga parviflora*, 27 – *Galium aparine*, 28 – *Lactuca serriola*, 29 – *Lamium amplexicaule*, 30 – *Lamium purpureum*, 31 – *Lepidium campestre*, 32 – *Lepidium draba*, 33 – *Lepidium ruderale*, 34 – *Panicum capillare*, 35 – *Papaver rhoeas*, 36 – *Poa annua*, 37 – *Polygonum aviculare*, 38 – *Polygonum convolvulus*, 39 – *Polygonum lapathifolium*, 40 – *Portulaca oleracea*, 41 – *Raphanus raphanistrum*, 42 – *Raphanus sativus* L. var. *oleiformis*, 43 – *Senecio vernalis*, 44 – *Setaria glauca*, 45 – *Setaria viridis*, 46 – *Sinapis alba*, 47 – *Sinapis arvensis*, 48 – *Sisymbrium loeselii*, 49 – *Solanum nigrum*, 50 – *Spergula vulgaris*, 51 – *Stellaria media*, 52 – *Thlaspi arvense*, 53 – *Tripleurospermum maritimum*, 54 – *Veronica hederifolia*

Weeds dominating the oilseed radish agrophytocoenosises in our research for criterion of frequency of appearance (F, Table 1) belong to both the third and the second groups mentioned above. Hence, the success of their invasion could be due, at least in part, to their allelopathic effects. At the same time, for an extract concentration of 0.25%, the criterion 'seed germination rate' was not significantly different from the control (10.43–11.00 seeds.day^{-1}) for a number of species (p >0.05), including *Aethusa cynapium*, *Berteroa incana*, *Bunias orientalis*, *Centaurea cyanus*, *Daucus carota*, *Papaver rhoeas*, *Setaria viridis*, *Sisymbrium loeselii*, *Spergula vulgaris*, *Veronica hederifolia*.These species had a lower prevalence in agrophytocenoses of oil radish of different technological design (Tsytsiura, 2021), which confirms the statement about the relationship between the frequency of occurrence of this weed in the cenosis and the nature of its allopathic potential of stimulating or depressing nature (Smith, 2013). This effect was also positively correlated with the findings on the stimulating effect of aqueous extracts of weeds at low concentrations in the range of 0.01–0.10% (Duke, 2015; Abbas et al., 2021; Chaves et al., 2023). Oilseed radish seeds required 5–6 days for full germination in distilled water. However, this time was extended to 7–9 days when seeds were exposed to some weed extracts. This situation is visualized in Figure 3 where average CV_i values of the 54 weed extracts recorded from day 3rd to 9th show greater standard deviations at the concentration of 4% than at 1%. Hence, increasing concentrations augmented delays in germination which were specific of the weed extract tested (Duke, 2015; Choudhary et al., 2023). At the same time, the maximum range of values for both concentration variants is determined on the 3rd and 4th day of germination. The decrease in the concentration of the applied extract reduced the allelopathic pressure and normalized the variable dynamic curve of germinated seed formation to the biologically optimal maximum similarity on the 3–5th day in the absence of allelopathic extracts. This is more clearly observed in Figure 4 showing CV_i values obtained when oilseed radish was germinated in distilled water (control) and some weed extracts at the concentration of 4%. Control treatment showed a maximum germination rate at day 5th while weed extracts reduced the magnitude of the maximum rate at such day or shifted

it to a later day. Most of them increased the timespread needed to end the germination respect to control from day 7th to 9th. The pattern of CV_i values recorded for the weed extracts at the concentration of 1% was near to that observed in the control. The changes in the CV_i values observed for the weed extracts at high and low concentrations agree with results obtained by other researchers (Reigosa et al., 2006; Możdżeń et al., 2018; Marinov-Serafimov et al., 2019; Carvalho et al., 2019; Begum et al., 2021) and need further research in order to elucidate how they were influenced by pH, osmotic potential and allelochemicals.

The weed species were grouped based on their APG indexes calculated for oilseed radish in Petri plate and soil bioassays. Table 4 shows the weed species grouped in an APG scale of ten intervals. A weed species belonging to a scale cluster based on Petri plate bioassays, often is grouped in a contiguous lower APG interval defined by soil bioassays. A longer distance is observed between

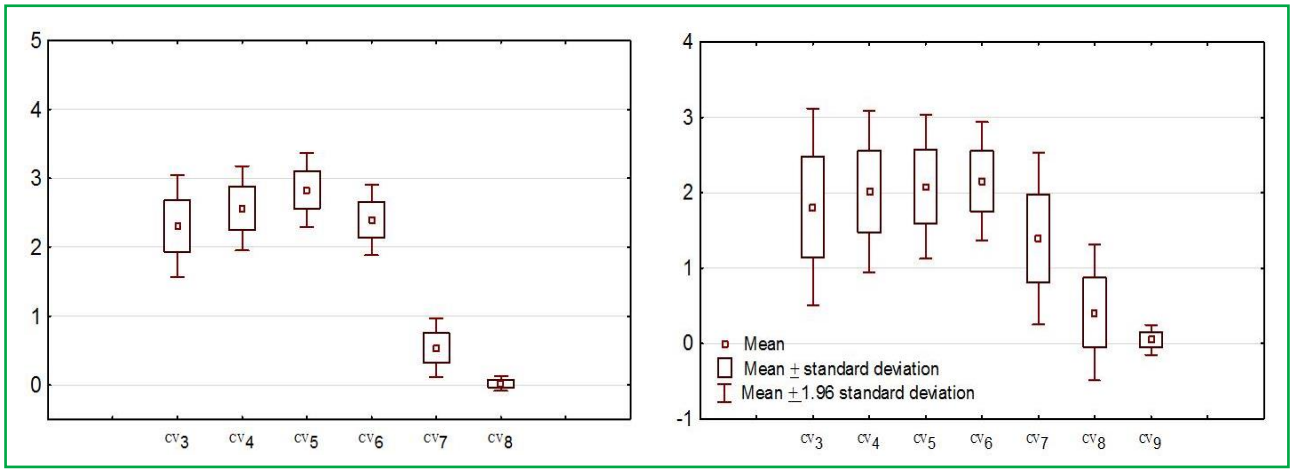

Figure 3 Span diagrams obtained for the means of the coefficient of velocity (CV_i) calculated from the third (CV_3) to the ninth day (CV_9) of oilseed radish germination
on the left – weed extract concentration 1%, on the right – 4%

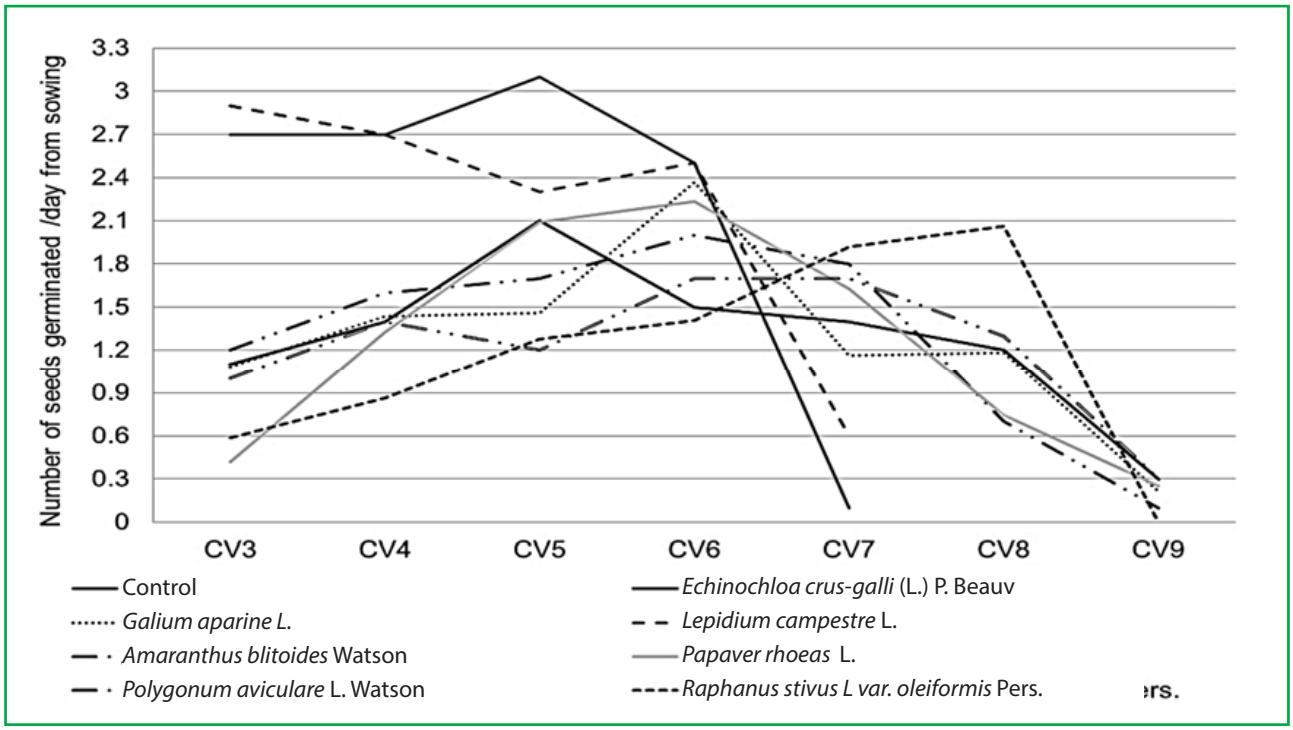

Figure 4 Effects of some weed extracts at the concentration of 4% on Coefficient of velocity (CV_i) recorded for oilseed radish germination from day 3 (CV_3) to day 9 (CV_9)

Petri plate and soil AP indexes for few species such as *Setaria glauca* and *Capsella bursa-pastoris* and *Echinochloa crus-galli*.

These species belong to the herbological forms with dominant vitality tactics in all tiers of high-altitude plant development (Zimdahl, 2018), in particular in the phase of seedlings – the formation of the rosette in the oilseed radish (BBCH 14-20), and the middle tier in the phase of stem formation-beginning of budding of oilseed radish plants (BBCH 26-50). During the maturation period (BBCH 83-89), such species as *Setaria glauca* and *Echinochloa crus-galli* occupy the dominant upper tier (Tsytsiura, 2021). It should be noted from clustering presented in Table 4 that the highest APG values for seed germination obtained in Petri plate bioassays were recorded for the species most commonly found at the our experimental fields in the oilseed radish agrophytocoenosises.

However, some of them should be excluded (e.g. *Portulaca oleracea*, *Aethusa cynapium*) because they are mostly absent in the oilseed radish cenosis. Other species also included in this group are considered both regular weeds and culturally related species, which are studied in the self-seeding or as fallen residues (e. g. *Brassica napus*, *Barbarea vulgaris*, *Sinapis arvensis*, *Brassica campestris* and *Raphanus raphanistrum*). At the same time, the maximum AP value at germination on both substrates (0.68, Petri plate bioassays; 0.72, soil bioassays) was noted for oilseed radish extracts. This situation agrees with previous researchs and emphasizes the high degree of autotoxicity observed in cruciferous species at germination (Lawley et al., 2012; Rueda-Ayala et al., 2015; Manivannan et al., 2019; Bolouri et al., 2022). Weed species clustered in the APG intervals in the range 0.26–0.50 have a low occurrence in the agrophytocoenosis of oilseed radish

Table 4 Allelopathic potential of weed extracts calculated for seed germination (APG) of oilseed radish (BBCH 01–05)

APG interval	Weeds in Petri plate bioassays	N of spp.	Weeds in the soil bioassays	N of spp.
0.26–0.30	–		*Lepidium campestre*, *Poa annua*	2
0.30–0.35	*Erigeron canadensis*, *Lepidium campestre*, *Poa annua*	3	*Centaurea cyanus*, *Erigeron canadensis*, *Lactuca serriola*, *Setaria glauca*, *Stellaria media*	5
0.36–0.40	*Centaurea cyanus*, *Erodium cicutarium*, *Lactuca serriola*, *Stellaria media*	4	*Daucus carota*, *Erodium cicutarium*, *Lamium purpureum*, *Lepidium ruderale*, *Panicum capillare*, *Spergula vulgaris*	6
0.41–0.45	*Bromus secalinus*, *Daucus carota*, *Lamium purpureum*, *Lepidium ruderale*, *Panicum capillare*, *Spergula vulgaris*, *Setaria glauca*, *Veronica hederifolia*	8	*Bromus secalinus*, *Crepis tectorum*, *Eryngium campestre*, *Lamium amplexicaule*, *Polygonum aviculare*, *Polygonum lapathifolium*, *Veronica hederifolia*	7
0.46–0.50	*Berteroa incana*, *Bunias orientalis*, *Crepis tectorum*, *Digitaria ischaemum*, *Eryngium campestre*, *Lamium amplexicaule*, *Polygonum aviculare*	7	*Ambrosia artemisiifolia*, *Avena fatua*, *Berteroa incana*, *Bunias orientalis*, *Capsella bursa–pastoris*, *Descurainia sophia*, *Digitaria ischaemum*, *Echinochloa crus–galli*, *Galium aparine*, *Setaria viridis*, *Senecio vernalis*, *Thlaspi arvense*	12
0.51–0.55	*Ambrosia artemisiifolia*, *Avena fatua*, *Chondrilla juncea*, *Descurainia sophia*, *Polygonum lapathifolium*, *Senecio vernalis*, *Setaria viridis*, *Solanum nigrum*, *Thlaspi arvense*	9	*Aethusa cynapium*, *Brassica napus*, *Chondrilla juncea*, *Lepidium draba*, *Sisymbrium loeselii*, *Solanum nigrum*	6
0.56–0.60	*Aethusa cynapium*, *Barbarea vulgaris*, *Brassica napus*, *Capsella bursa-pastoris*, *Echinochloa crus-galli*, *Galium aparine*, *Lepidium draba*, *Polygonum convolvulus*, *Portulaca oleracea*, *Sisymbrium loeselii*	10	*Amaranthus blitoides*, *Barbarea vulgaris*, *Brassica campestris*, *Consolida regalis*, *Fumaria officinalis*, *Galinsoga parviflora*, *Polygonum convolvulus*, *Portulaca oleracea*, *Sinapis alba*, *Tripleurospermum maritimum*	10
0.61–0.65	*Amaranthus blitoides*, *Fumaria officinalis*, *Galinsoga parviflora*, *Sinapis alba*, *Sinapis arvensis*, *Consolida regalis*, *Tripleurospermum maritimum*	7	*Amaranthus retroflexus*, *Chenopodium album*, *Papaver rhoeas*, *Raphanus raphanistrum*, *Sinapis arvensis*	5
0.66–0.70	*Amaranthus retroflexus*, *Brassica campestris*, *Chenopodium album*, *Papaver rhoeas*, *Raphanus raphanistrum*	5	*Raphanus sativus*. var. *oleiformis*	1
0.71–0.75	*Raphanus sativus* var. *oleiformis*	1	–	–

(Lawley et al., 2012) (e.g. *Lamium purpureum*, *Centaurea cyanus*, *Erigeron canadensis*) or belong to the types of weeds occupied by the ground or lower vegetation layer in the phytocenosis of the oilseed radish (e.g. *Stellaria media*, *Poa annua*, *Lepidium campestre*). The likelihood of allelopathic interference of these weeds during oilseed radish germination is very low. Hence, from an allelopathic point of view, appropiate timing of oilseed radish sowing likely should aid to control them. Altogether, the APG indexes suggest that the effectiveness of oilseed radish to control weeds strongly depends on the weed species contaminating the field at the beginning of oilseed radish growth.

Biomass allocation to plant organs is a key process which affect plant growth and reproduction (Lorenzo et al., 2013). It greatly vary among terrestrial plants according to a complex set of ontogenical and environmental factors where allelopathy also is often involved (Carvalho et al., 2019; Chaves et al., 2023). For this reason, we decided to test the impact of the aqueous weed extracts on growth processes of oilseed radish. Table 5 shows that the extracts of 31 weed species (57.5% of the total tested) augmented shoot participation in the total seedling elongation respect to the controls, especially when concentration increased, with strong interspecific variations in the magnitude of the increase. This finding is expectable if we consider that roots are the main action site of allelochemicals in receptor terrestrial plants (G´amiz et al., 2019). However, extracts of 12 weed species reduced root elongation more than shoot length while 10 weed extracts maintained the same participation of roots and shoots in total seedling elongation as in the controls. In the case of dry weight, extracts from 39 weed species reduced dry biomass allocation in shoots respect to controls, while those of 10 and 5 weed species did not modify and increased it, respectively. The lowest and highest inhibitory effects of each weed extract were obtained at 1.0 and 4.0%, respectively (Table 5).

Table 6 presents the allelopathic potential indexes for root (APGR) and short growth (APSG). Extracts from weed species showing the lowest APGR or APSG indexes had the maximum differences between their values recorded at the concentrations of 1.0 and 4.0% (e. g. *Erigeron canadensis*, *Poa annua*, *Lepidium campestre* and *Daucus carota*). The weed extracts with the highest allelopathic activity showed minimum differences (e. g. *Brassica campestris*, *Brassica napus*). It should be noted that APGR values were very different from the APSG values. This situation confirms the modifications in biomass allocation and elongation produced in shoots and roots by several weed extracts which is confirmed by the data of interval grouping of APGR and APSG indexes. At the same time it was noted (in view of Smith, 2013) that the AP indicator is a measure of the overall allelopathic effect of relationships in the system weed-tester plant, and in the variant of determining the indicators of allelopathic pressure by laboratory germination indicators and initial growth, showing the level of competitiveness of the tester plant in relation to a particular type of weed ignoring the rate of vegetative growth of the tester, the level of its vitality tactics and other factors. Also noted (Lorenzo et al., 2013; Marinov-Serafimov et al., 2019) that it clearly divides species by thresholds values of important starting competition, which determines the subsequent success of the formation of agrophytocoenosis of any crop plant. According to the proposed gradation of Smith (2013) and the assessments of other scientists (Reigosa et al., 2006; Fujii & Hiradate, 2007; Lorenzo et al., 2013), in terms of the ratio of weeds with the AP level above and below 0.5, oilseed radish can be attributed to species with high herbal competition potential, where this indicator was 0.75.

According to our results, weeds can be grouped in (Table 7):

a) species that strongly inhibit the primary root system of oilseed radish (for example, *Brassica napus* L., *Lepidium draba* L., *Amaranthus blitoides* Watson, *Amaranthus retroflexus* L., *Brassica campestris* (L.) Janchen, *Echinochloa crus-galli* (L.) P.Beauv., *Erigeron canadensis* L., *Senecio vernalis* (Waldstein & Kitaibel) Alexander, *Sinapis alba* L., *Sisymbrium loeselii* L., *Stellaria media* (L.) Vill.);
b) species that inhibit seedling growth (*Descurainia sophia* (L.) Prantl, *Fumaria officinalis* L., *Galinsoga parviflora* Cavanilles, *Portulaca oleracea* L., *Raphanus sativus* L. var. *oleiformis* Pers.);
c) species that reduce in an equal extent both root and sprout growth (*Panicum capillare* L., *Setaria viridis* (L.) Palisot de Beauvois).

This fact does possible to calculate APGR/APSG ratios which can be used to assess oilseed radish allometry exerted by the weeds at single or multi-species integrated levels.

The average value of APGR and APSG indicated values higher than 0.5 for dominant weeds in different periods of growth and development of oilseed radish plants. These species include *Echinochloa crus-galli*, *Chenopodium album*, *Polygonum convolvulus*, *Amaranthus retroflexus* and *Galinsoga parviflora*. The species botanically similar to the oilseed radish (e.g. *Brassica napus*, *Sinapis alba*) also demonstrated a high allelopathic potential.

Our results suggest that the most harmful competitive weeds found in oilseed radish agrophytocoenosises also exert a strong allelopathic pressure confirmed in the case of perennial weed species (Tsytsiura, 2022). Based on

Table 5 Effect of weed aqueous extracts tested at concentrations of 1% and 4% (w/v) on seedling growth of oilseed radish in soil bioassays

Species number (according to Table 1)	Length (mm)				Dry weight (g)			
	root		stem		root		stem	
	1%	4%	1%	4%	1%	4%	1%	4%
Control	30.2	30.2	80.2	80.2	3.94	3.58	23.70	16.56
1	17.7	7.4	55.5	31.4	2.30	1.25	16.41	6.49
2	14.3	7.4	42.4	25.2	1.87	1.21	12.52	5.20
3	14.0	8.0	45.7	37.2	1.82	1.34	13.51	7.68
4	15.9	10.9	58.3	41.4	2.07	1.61	17.22	8.55
5	21.7	11.1	38.3	26.9	2.83	2.02	11.30	5.55
6	22.9	6.9	39.4	31.0	2.99	1.54	11.65	6.40
7	23.0	15.2	56.3	31.2	3.01	2.10	16.64	6.45
8	13.6	10.1	48.9	36.5	1.77	1.42	14.43	7.53
9	12.1	7.8	42.1	22.0	1.59	1.18	12.44	4.53
10	16.9	14.8	42.9	32.2	2.21	1.69	12.67	6.65
11	15.1	8.8	57.8	42.2	1.97	1.39	17.06	8.71
12	17.0	10.5	71.0	64.2	2.22	1.87	22.75	13.26
13	15.9	8.1	46.8	39.3	2.07	1.32	13.83	8.10
14	23.9	11.7	56.4	32.3	3.11	2.43	16.66	6.66
15	15.9	9.7	47.2	33.7	2.08	1.60	13.94	6.96
16	17.2	10.3	54.8	36.7	2.24	1.87	16.19	7.56
17	20.3	12.0	48.9	34.7	2.65	2.02	14.46	7.17
18	7.9	16.0	42.8	55.7	2.09	1.43	16.45	8.83
19	18.1	10.1	36.5	24.3	2.36	1.43	10.77	5.01
20	16.8	8.8	40.1	30.1	2.20	1.76	11.84	6.22
21	13.9	6.9	54.8	40.7	1.81	1.34	16.18	8.39
22	14.6	8.2	60.1	40.8	1.90	1.33	17.76	8.42
23	18.5	12.2	54.2	39.3	2.41	2.00	16.00	8.11
24	26.0	13.1	46.6	29.2	3.40	2.25	13.78	6.03
25	17.4	8.1	38.8	21.6	2.28	1.63	11.47	4.46
26	27.9	10.2	37.2	21.6	3.64	1.79	11.00	4.45
27	23.9	13.8	72.7	44.9	3.12	2.19	22.14	9.28
28	16.2	10.0	40.1	29.8	2.11	1.57	11.83	6.15
29	18.4	11.4	59.1	37.4	2.40	1.86	17.45	7.72
30	19.2	11.1	45.0	27.3	2.51	1.68	13.28	5.64
31	20.8	12.0	56.6	35.1	2.71	1.91	16.71	7.25
32	11.5	5.8	39.6	29.3	1.50	1.16	11.69	6.05
33	23.7	11.3	51.4	37.6	3.09	2.05	15.17	7.76
34	20.5	12.4	50.7	38.8	2.67	2.11	14.98	8.00
35	26.0	15.9	55.3	31.9	3.39	2.46	16.33	6.58
36	20.1	14.0	45.7	35.0	2.63	1.98	13.50	7.22
37	19.1	10.3	54.8	31.2	2.50	1.71	16.18	6.43
38	16.1	12.0	42.6	27.8	2.10	1.46	12.58	5.73

Continuation of Table 5

Species number (according to Table 1)	Length (mm)				Dry weight (g)			
	root		stem		root		stem	
	1%	4%	1%	4%	1%	4%	1%	4%
39	24.8	13.9	53.1	30.4	3.24	2.12	15.70	6.27
40	22.3	12.0	35.2	27.2	2.91	2.04	10.40	5.62
41	23.2	12.0	56.3	40.5	3.03	2.15	16.63	8.35
42	15,7	9.6	41.8	23.1	3.13	2.38	14.05	5.80
43	15.4	8.3	41.4	33.2	2.01	1.35	12.23	6.85
44	25.4	13.6	61.0	34.0	3.32	2.4	18.03	7.01
45	21.0	12.0	50.5	40.5	2.74	1.86	14.90	8.36
46	14.2	7.3	40.6	22.9	2.44	1.78	15.30	7.58
47	18.7	9.4	51.8	36.7	1.86	1.35	11.98	4.72
48	15.2	8.3	56.7	40.4	1.98	1.46	16.74	8.34
49	18.1	8.6	59.3	41.9	2.36	1.59	17.52	8.65
50	19.4	11.2	60.6	41.8	2.53	1.85	17.91	8.63
51	13.4	8.0	56.7	42.8	1.75	1.34	16.75	8.83
52	20.5	10.0	58.4	35.5	2.68	1.51	17.26	7.34
53	28.1	18.9	43.9	27.8	3.66	2.75	12.97	5.74
54	17.8	13.7	45.1	24.2	2.33	1.92	13.33	5.00
Tukey's test 95% family-wise confidence level (interval min. level of allowable difference for p_{adj})	0.72–1.58	1.26–2.11	2.17–2.81	1.88–2.74	0.57–0.89	0.12–0.27	0.63–1.17	0.47–0.85

Table 6 Allelopathic potential on root and stem growth (APRG and APSG, respectively) of oilseed radish calculated for weed extracts in soil bioassay on oilseed radish

*No spp.	APRG	APSG	*No spp.	APRG	APSG	*No spp.	APRG	APSG	*No spp.	APRG	APSG
1	0.58	0.46	15	0.58	0.50	29	0.51	0.40	43	0.61	0.53
2	0.64	0.58	16	0.55	0.43	30	0.50	0.55	44	0.35	0.41
3	0.64	0.48	17	0.46	0.48	31	0.46	0.43	45	0.45	0.43
4	0.56	0.38	18	0.60	0.39	32	0.71	0.57	46	0.64	0.60
5	0.46	0.59	19	0.53	0.62	33	0.42	0.45	47	0.53	0.45
6	0.50	0.56	20	0.58	0.56	34	0.45	0.44	48	0.61	0.39
7	0.37	0.45	21	0.65	0.41	35	0.31	0.46	49	0.56	0.37
8	0.61	0.47	22	0.62	0.37	36	0.43	0.50	50	0.49	0.36
9	0.67	0.60	23	0.49	0.42	37	0.51	0.46	51	0.64	0.38
10	0.47	0.53	24	0.35	0.53	38	0.53	0.56	52	0.49	0.41
11	0.60	0.38	25	0.58	0.62	39	0.36	0.48	53	0.22	0.55
12	0.54	0.16	26	0.37	0.63	40	0.43	0.61	54	0.48	0.57
13	0.60	0.46	27	0.37	0.27	41	0.42	0.40	LSD0/05	0.032	0.041
14	0.47	0.55	28	0.57	0.56	42	0.58	0.65			

* serial number of the weed species according to Table 1

Table 7 Weed species grouped according to their allelopathic potential (APRG and APSG, respectively) on initial growth of oilseed radish (BBCH 01-12)

Interval	Weed species clustered into each interval	N of spp.		N of spp.
	APRG		APSG	
< 0.30	*Tripleurospermum maritimum*	1	*Capsella bursa-pastoris*, *Galium aparine*	2
0.30–0.35	*Eryngium campestre*, *Papaver rhoeas*, *Setaria glauca*	3	–	–
0.36–0.40	*Berteroa incana*, *Galinsoga parviflora*, *Galium aparine*, *Polygonum lapathifolium*	4	*Ambrosia artemisiifolia*, *Bunias orientalis*, *Daucus carota*, *Erigeron canadensis*, *Lamium amplexicaule*, *Raphanus raphanistrum*, *Sisymbrium loeselii*, *Solanum nigrum*, *Spergula vulgaris*, *Stellaria media*	10
0.41–0.45	*Lepidium ruderale*, *Panicum capillare*, *Poa annua*, *Portulaca oleracea*, *Raphanus raphanistrum*, *Setaria viridis*	6	*Berteroa incana*, *Crepis tectorum*, *Echinochloa crus-galli*, *Erodium cicutarium*, *Lepidium campestre*, *Lepidium ruderale*, *Panicum capillare*, *Setaria glauca*, *Setaria viridis*, *Sinapis arvensis*, *Thlaspi arvense*	11
0.46–0.50	*Avena fatua*, *Barbarea vulgaris*, *Bromus secalinus*, *Chenopodium album*, *Consolida regalis*, *Erodium cicutarium*, *Lamium purpureum*, *Lepidium campestre*, *Spergula vulgaris*, *Thlaspi arvense*, *Veronica hederifolia*	11	*Aethusa cynapium*, *Amaranthus retroflexus*, *Brassica campestris*, *Centaurea cyanus*, *Chondrilla juncea*, *Consolida regalis*, *Papaver rhoeas*, *Poa annua*, *Polygonum aviculare*, *Polygonum lapathifolium*	10
0.51–0.55	*Capsella bursa-pastoris*, *Crepis tectorum*, *Descurainia sophia*, *Lamium amplexicaule*, *Polygonum aviculare*, *Polygonum convolvulus*, *Sinapis arvensis*	7	*Bromus secalinus*, *Chenopodium album*, *Eryngium campestre*, *Lamium purpureum*, *Senecio vernalis*, *Tripleurospermum maritimum*	6
0.56–0.60	*Aethusa cynapium*, *Ambrosia artemisiifolia*, *Bunias orientalis*, *Centaurea cyanus*, *Chondrilla juncea*, *Daucus carota*, *Digitaria ischaemum*, *Fumaria officinalis*, *Lactuca serriola*, *Raphanus sativus* var. *oleiformis*, *Solanum nigrum*	11	*Amaranthus blitoides*, *Avena fatua*, *Barbarea vulgaris*, *Brassica napus*, *Digitaria ischaemum*, *Lactuca serriola*, *Lepidium draba Polygonum convolvulus*, *Sinapis alba*, *Veronica hederifolia*	10
0.61–0.65	*Amaranthus blitoides*, *Amaranthus retroflexus*, *Brassica campestris*, *Echinochloa crus-galli*, *Erigeron canadensis*, *Senecio vernalis*, *Sinapis alba*, *Sisymbrium loeselii*, *Stellaria media*	9	*Descurainia sophia*, *Fumaria officinalis*, *Galinsoga parviflora*, *Portulaca oleracea*, *Raphanus sativus* var. *oleiformis*	5
0.66–0.70	*Brassica napus*	1	–	–
>0.70	*Lepidium draba*	1	–	–

the AP indexes calculated, weeds can be classified from more to less harmful, with the maximum allelopathic pressure matching with the strongest coenotic pressure in cenosis. In such context, these species should exert a strong allelopathic effect on the crop when a third of them appears in the oilseed radish phytocenosis.

The data obtained is also confirmed by the level of allelopathic effect on other cultivated plants from a number of weed species under study, including the representatives of the Convolvulaceae (COVF) family in the studies of Marinov-Serafimov et al. (2017); Brassicaceae (1CRUF) family species in the studies of Lawley et al. (2012), El-Gawad (2014), Lemerle et al. (2017), Marinov-Serafimov et al. (2019); Poaceae (1GRAF) family species in the studies of Marinov-Serafimov et al. (2017); Apiaceae (1UMBF) family species in the studies of Lorenzo et al. (2013); Asteraceae (1COMF) family species in the studies of Możdżeń et al. (2018), Marinov-Serafimov et al. (2019); Amaranthaceae (1AMAF) family species in the studies of Prinsloo and Plooy (2018), Carvalho et al. (2019), VanVolkenburg et al. (2020); Polygonaceae (1POLF) family species in the studies of Lorenzo et al. (2013). According to the research results of the above-mentioned authors, the highest level of allelopathic potential was noted for the Asteraceae and Poaceae family representatives, and among the parasitic representatives of the Convolvulaceae family.

The data obtained also allowed to determine the most harmful type of contamination for oilseed radish agrophytocoenosises, which is based on estimates of

the level of competitive and allelopathic pressure, given the previously studied vitality tactics of a variety of weed species in the oilseed radish cenosises of different technological density (Tsytsiura, 2020), as well as estimated in other studies (Smith, 2013; Zimdahl, 2018) on the formation of competitive relationships and the degree of dominance of weed in different agrophytocoenosises. In this regard, for oilseed radish in view of the AP of the studied species, the total harmfulness of the types of infestation will increase in the following order: young – rhizomatous – young-rhizomatous, soboliferous, young-soboliferous – rhizomatous-soboliferous – young-soboliferous-rhizomatous. At the same time, the maximum allelopathic pressure will be noted by analogy with the coenotic pressure in cenosis (Macias et al., 2003) provided that participation in the formation of stem and cenosis tiers of one-third of species with AP level from 0.5.

This is confirmed by the results of plane regression visualization and analysis between the long-term average of the criterion of frequency of appearance (F) (Table 1) for the studied weed species and the parameters APG (Petri dish bioassays), APG (Soil bioassays), APRG, APSG determined for them on the test object of oilseed radish (Figure 5).

Graphical visualization showed the complex nature of the relationships between the indicators, which is confirmed by the power law nature of the equation in the system of multivariate regression analysis and the reliable value of the multiple regression coefficient (*R*). The tendency of growth of allelopathic potential (AP) species in a single or binary character is characteristic of weed species in the agrocenosis of oil radish that have a higher frequency of accounting in the composition of the total stem of the crop. At the same time, the higher value of the multiple regression coefficient (R) in the variant of applying the criteria of allopathic potential by assessing the allometry of root systems and seedlings (APRG and APSG) indicates the resulting effect of the realization of the allopathic potential of weeds at the stage of initial growth processes. This fact was pointed out in their studies by Smith (2013) and Far (2018).

The complex curved reaction surface of the plane formed by the indicators in the regression study confirmed the opinion of Fujii & Hiradate (2007) that the allopathic interaction in the plant-weed system with the assessment of the cenotic prevalence of a particular species cannot be considered without the factor of systemic interaction between all species that form a certain living space on which the frequency of prevalence of individual species is analyzed. That is, the actual prevalence of a particular weed species in the cenosis of a particular crop will be

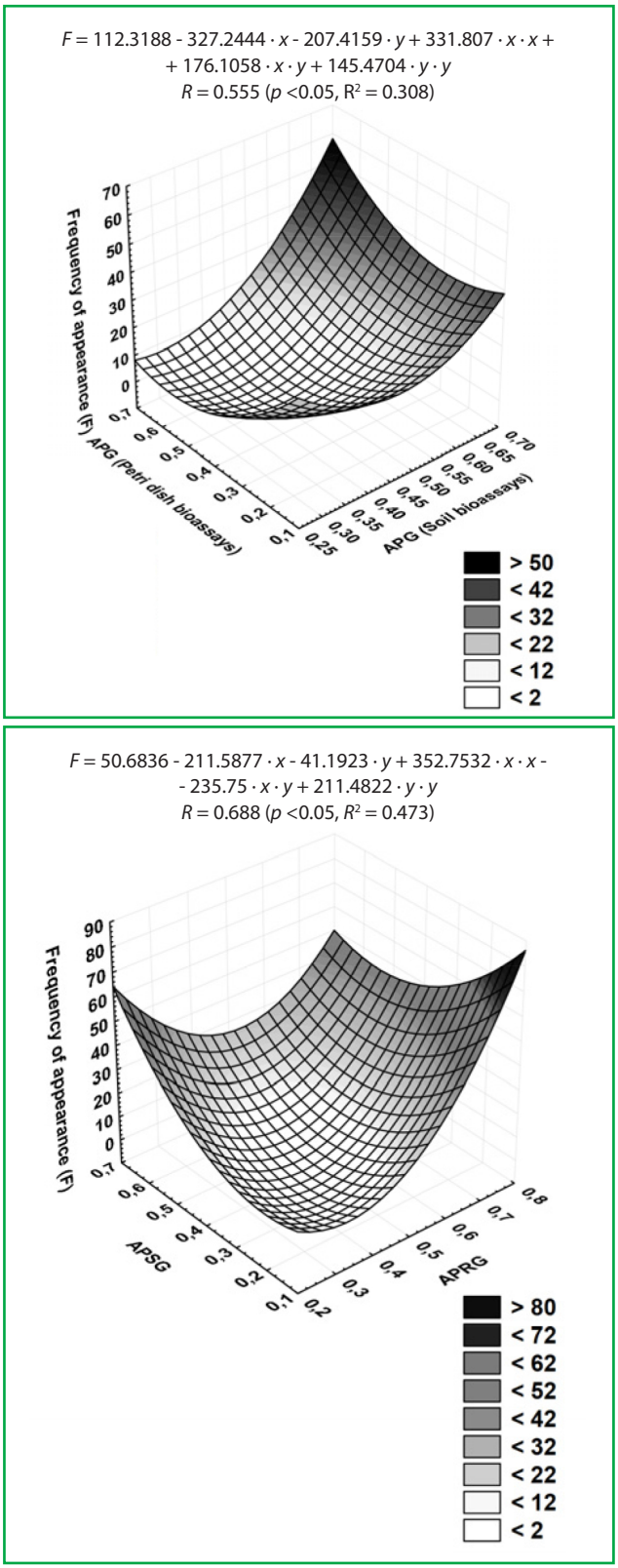

Figure 5 Graphical expression of the dependence of the average long-term frequency of appearance (F) for the studied weed species in the oil radish agrophytocenosis on the APG (Petri dish bioassays) and APG (Soil bioassays) indicators – top position, APRG and APSG – lower position

determined by the direction of the resulting vector of complex interaction in accordance with the life strategies of each species, which depend on the allopathic tension of the polyvalent nature of simultaneous growth and development. This is confirmed by the studies of Begum et al. (2021), Carvalho et al. (2019), Khamare et al. (2023), and Chaves et al. (2023).

At the same time, the use of regression analysis in the application to weed species of oil radish agrocenosis confirmed that the criterion of allopathic potential can be used to predict the prevalence of segetal vegetation species in the cenosis of the test crop. At the same time, the task that needs to be solved is to form the place of the AP indicator in the model of the prevalence of certain weed species in the most objective way, taking into account the agrotechnological aspects of the formation of the cenosis of the corresponding test crop. The construction of such a model is possible and, based on the presented results, will have a complex stepwise character with the obligatory inclusion of hydrothermal and edaphic factors of plant growth and development. The importance of edaphic factors is confirmed by the results of Table 1, where the frequency of occurrence of different types of weeds varied depending on the nature of the pre-sowing design of oil radish agrocenosis, respectively, its minimum and maximum agrotechnological density. This is the direction highlighted in the studies of Iqbal et al. (2021) and is a prospect for further research in the field of allopathic control of weed infestation in agrophytocenoses of cultivated plants.

4 Conclusions

Oilseed radish was very sensitive to the water extracts of the 54 weed species tested in the range of concentrations 0.25–16% (w/v). Soil alleviated the allelopathic impact of the weed extracts. APG indexes allowed to cluster weed extracts in 10 intervals of 0.05 included in the range 0.26–0.72.

Twenty seven species (50.0% of the total tested) had APG values higher than 0.50. The APG values calculated from data recorded from Petri dish and soil bioassays allow to classify the weed species from more to less harmful on oilseed radish, in the following order: *Raphanus sativus* L. var. *oleiformis* Pers. (0.68–0.72) > *Amaranthus retroflexus* L. (0.64–0.67) > *Chenopodium album* L. (0.63–0.67) > *Raphanus raphanistrum* L. (0.63–0.67) > *Papaver rhoeas* L. (0.61–0.68) > *Brassica campestris* (L.) Janchen (0.60–0.67) > *Brassica napus* L. (0.60–0.67) > *Sinapis arvensis* L. (0.62–0.64) > *Sinapis alba* L. (0.59–0.62) > *Fumaria officinalis* L. (0.60–0.62) > *Galinsoga parviflora* Cavanilles (0.57–0.62) > *Tripleurospermum maritimum* (L.) Koch (0.57–0.61) > *Portulaca oleracea* L. (0.57–0.60) > *Barbarea vulgaris* Brown (0.56–0.59) > *Lepidium draba*. L. (AP = 0.54–0.57) > *Brassica napus* L. (0.53–0.57) > *Sisymbrium loeselii* L. (0.54–0.57) > *Chondrilla juncea* L. (0.52–0.55) > *Galium aparine* L. (0.49–0.58) > *Echinochloa crus-galli* (L.) P.Beauv. (0.47–0.57) > *Senecio vernalis* (Waldstein & Kitaibel) Alexander (0.50–0.52) > *Solanum nigrum* L. (0.54–0.55) > *Descurainia sophia* (L.) Prantl (0.49–0.53) > *Thlaspi arvense* L. (0.46–0.52).

The weeds were classified according to their APSG and APRG indexes, and the percentage of appearance frequency (F) in oilseed radish fields, from more to less harmful, as: *Amaranthus retroflexus* (0.48, 0.64, 62.33–71.67) > *Echinochloa crus-galli* (L.) P.Beauv (0.41, 0.65, 58.67–71.67%) > *Setaria glauca* L. (0.53, 0.61, 56.00–62.33%) > *Chenopodium album* L. (0.55, 0.47, 42.67–54.00%) > *Brassica napus* L. (0.60, 0.67, 5.00–53.50%) > *Galinsoga parviflora* Cavanilles (0.63, 0.37, 25.00–46.33%) > *Sinapis alba* L. (0.60, 0.64, 4.30–42.80%) > *Tripleurospermum maritimum* (L.) Koch (0.41, 0.49, 16.33–42.67%) > *Raphanus sativus* L. var. *oleiformis* Pers. (0.65, 0.58, 3.50–40.70%) > *Polygonum lapathifolium* (L.) Delarbre (0.48, 0.36, 24.67–34.33%) > *Setaria viridis* (L.) Palisot de Beauvois (0.41, 0.35, 16.67–25.00%) > *Barbarea vulgaris* Brown (0.56, 0.50, 6.67–22.67%) > *Brassica campestris* (L.) Janchen (0.47, 0.61, 19.33–22.33%) > *Lactuca serriola* L. (0.56, 0.57, 10.67–21.67%) > *Thlaspi arvense* L. (0.38, 0.64, 7.67–21.0%) > *Senecio vernalis* (Waldstein & Kitaibel) Alexander (0.65, 0.58, 11.00–17.67%) > *Lepidium draba* L. (0.57, 0.71, 7.11–8.92%).

Considering the obtained allelopathic potential for different types of weeds, the maximum harmfulness of weed cenosis in the oilseed radish agrophytocoenosises will be noted if there were 30% of weeds with APG (APRG, APSG) level 0.5 in case of young-soboliferous-rhizomatous type of infestation. This was confirmed by the results of regression analysis with the level of multiple regression coefficient (R) in the range of 0.555–0.688 (p <0.05) in the system of comparing the frequency of appearance (F) (the resulting trait) and the studied types of allopathic potential (APG (Petri dish bioassays), APG (Soil bioassays), APRG, APSG).

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