



Allelopathic activity of coriander (*coriandrum sativum* L.)

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Received: 9 June 2024 / Accepted: 2 January 2025 / Published online: 10 February 2025

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Abstract

In recent years there has been increased interest about the allelopathic effects of plant extracts used as bioherbicides, in order to manage weeds with a decreasing use of herbicides. An interesting crop, from an allelopathic point of view, is coriander (*Coriandrum sativum* L.), a medicinal plant member of Apiaceae family. The aim of this study was to evaluate the allelopathic activity of coriander against a possible succeeding crop, like wheat (*Triticum aestivum* L.), and against some weeds, like *Lolium multiflorum* Lam., *Sinapis alba* L. and *Amaranthus retroflexus* L., ubiquitous in the Mediterranean agroecosystems. In Petri dish bioassays, seeds of above-mentioned species were treated with 0, 2.5, 5, 10, 17.5, 25% w/v concentrations of aqueous extracts from leaves, stems and roots of coriander at flowering and maturity growth stage. The ranking among different extracts based on their allelopathic effects was: leaves extract > stems extract > roots extract. The allelopathic activity of coriander at maturity stage decreased with respect to that at flowering stage. Total polyphenols, flavonoids and phenolic acids were involved in the allelopathic activity of coriander. The aqueous extracts from aerial biomass of coriander inhibited the seed germination of weeds, but not that of *T. aestivum*. This research has provided interesting scientific insights into the allelopathic activity of coriander in weed management, however, other aspects need to be further investigated.

Keywords Allelopathy · Sustainable weed management · Weeds · Bioherbicides · Natural herbicides · Allelochemicals

Introduction

Allelopathy is an ecological phenomenon that encompasses the positive and negative effects that one plant exerts on another one through the release of chemical compounds (allelochemicals) into the environment, and it has significant implications for natural ecosystems and agroecosystems (Rice 1984). Allelochemicals are secondary metabolites produced by plants that influence the biology of neighbouring organisms, with important ecological and agricultural implications (Li et al. 2010). Understanding this phenomenon is crucial for the development of sustainable agricultural practices (Mallik 2008). Among the most studied aspects are the outcomes on crop diseases and especially towards weeds, in order to understand the mechanisms and to develop possible practical implications for the benefit of farmers, through the inclusion of allelopathic species in rotation, or direct

application of plant derivatives. In fact, it is possible to exploit allelopathic effects in weed control, thus reducing the use of herbicides and promoting integrated and organic weed management in crop systems (Bhowmik and Inderjit 2003; Weston and Inderjit 2007; Nelson et al 2012; Pannacci et al. 2017). Interesting results were obtained by selecting allelopathic crop types and using allelopathic cover crops or phytotoxic crop residues (Kruidhof et al. 2014; Pannacci et al. 2013; Pheng et al. 2010). Furthermore, many researchers explored also the possibility of incorporating plant rests in the soil, using aromatic plants or eucalyptus leaves as green manure (Dhima et al. 2009; Puig et al. 2019). However, in recent years there has been increased interest about the allelopathic effects of plant extracts used as bioherbicides, in order to discover and understand the allelopathic potential towards weeds, as well as towards the main cultivated crops, with the main purpose of decreasing the use of synthetic herbicides through this possible alternative control tool (Soltys et al. 2013). In this regard, the hypothesis is accepted that weeds are most inhibited by allelochemicals at the seed stage or early growth stages, while being less susceptible at late growth stages (Kruse et al. 2000).

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The growing interest in alternative weed management methods to herbicides stems from the increasingly frequent cases of resistance by weeds to the most popular active ingredients and modes of action of herbicides. In fact, with chemical control, strong selective pressure is exerted in favour of weed genotypes that are resistant to the active ingredients used, consequently reducing the effectiveness of subsequently applied treatments (Abbas et al. 2018).

In Italy, for example, glyphosate-resistant populations have been found in three species, *L. multiflorum* (also in biotypes with cross-resistance to HRAC groups A and B), *Erygeron canadiensis* L., and *Lolium rigidum* Gaudin (Heap 2024). These populations were found in Apulian olive groves and Piemontese vineyards, agroecosystems where there is strong selective pressure due to the absence of rotations and almost exclusively chemical control with repeated applications of a single broad-spectrum total herbicide. In 1999, biotypes of common amaranth (*Amarantus retroflexus* L.) were found to show cross-resistance to HRAC C1 group herbicides in maize, soybean, and sugar beet; the same weed also showed resistance to the action of group B herbicides in soybean agroecosystems (Heap 2024).

In a context in which both major and minor arable crops are increasingly subjected to herbicide resistance to various modes of action, it turns out to be of paramount importance to develop an Integrated Weed Management System (IWMS). This method focuses at the implementation of measures that are both proactive, i.e. disfavours weed establishment, growth and competition, and reactive, i.e. direct and specific actions following the onset of the competitive problem (Zanin et al. 2024). In this regard, knowledge about allelopathic interactions can provide information both for a proper setting of the cropping system, with proactive measures, and find possible applications in reactive measures, contributing to the environmental and economic sustainability of production processes (Zanin et al. 2011).

Closely related to allelopathic interactions, the success of practices such as crop rotations or intercropping turns out to be strongly influenced by the presence of allelochemicals (Scognamiglio et al. 2013). Among the possible applications of these substances, there is their direct use in the form of aqueous extracts at different dosages obtained from crops with allelopathic effects towards certain weeds, applicable through direct distribution in the field, a solution that turns out to be a viable practice from both the environmental and economic points of view (Jamil et al. 2009; Maurya et al. 2024).

In this context, a crop of interest from an allelopathic point of view is coriander (*C. sativum*), a medicinal plant with a short 4-month cycle, that belongs to the Apiaceae family. It is an annual herb with origins from the Mediterranean area but widely cultivated in North Africa, Central Europe and Asia as a medicinal and food essence, that

grows excellently in a wide range of environmental conditions (Hammer 2004; Seidemann 2005). Coriander prefers cool, well-drained soils with pH between 6 and 7, suitable for warm-temperate climates with optimum germination temperatures around 12–15 °C; sowing is done in spaced rows with cereal seeder machine between March and April (Diederichsen 1996). Harvesting takes place between July and August on senescent plants through the use of harvesters, taking into consideration the degree of scalar ripening and drying of the fruits, which tend to shatter during the harvesting stage thus affecting yield and quality (Diederichsen 1996). Coriander has important pharmaceutical properties, but has received little attention from the allelopathic point of view in plant-plant interactions, resulting in a scarce supporting bibliography. Among the already existing findings it has been shown that coriander extracts have phenolic and flavonoids compounds which contribute to the antioxidative activity (Helle et al. 2004). For example, Dhima et al. (2009) demonstrated the allelopathic potential of coriander through experiments conducted both in the laboratory and in the open field, with comparative evaluation with other aromatic species. The authors recorded a decrease in the number of plants and fresh weight of *Chenopodium album* L. and a decrease in the number of plants of *Tribulus terrestris* L., reporting a consequent significant increase in both grain and silage maize production obtained from coriander compared to the untreated control. In the same trial, however, seeds of *Portulaca* spp. and *Echinochloa* spp. were found to be less inhibited. In a subsequent publication, it was indicated that coriander essential oil, under laboratory conditions, results in moderate inhibition on *Echinochloa* spp. when compared to those of essential oils of basil (*Ocimum basilicum* L.) and fennel (*Foeniculum vulgare* P. Mill.), while in the field the suppression was also found to be strongly greater due to the good competitive performance of the species compared to the other aromatics tested (Dhima et al. 2010). Iqbal et al. (2020) found that the treatment of coriander powder extracted affected root, shoot and seedling growth of *Vigna radiata* L. Wilczek, a legume crop named green bean. In particular, seedling dry mass of green gram significantly showed reduction with the treatment of coriander at 5% as compared to control (0%).

However, there are no studies on the allelopathic activity of the different parts of coriander plants at different growth stages on typical weed species in Mediterranean agroecosystems, whose research could represent an important step towards more sustainable weed management. Therefore, the aim of the present study was to evaluate the allelopathic activity of different parts of coriander (*C. sativum*) plants (leaves, stems and roots) at two different growth stages (flowering and harvesting) against a possible succeeding crop, like wheat (*T. aestivum*), and against some weeds, like

L. multiflorum, *S. alba* and *A. retroflexus*, ubiquitous in the Mediterranean agroecosystems.

Materials and methods

Plant sampling and aqueous extracts preparation

Plants of coriander (*C. sativum*) (variety 5909, Anseme S.p.a., Cesena, Italy) were collected from a cultivated field in a farm located in Collelungo, Castiglione del Lago (Perugia), central Italy (43°04'N, 12°02'E, 300 m a.s.l.), at two different growth stages: i) flowering stage and ii) harvest maturity stage. Fresh coriander plants at flowering stage were separated into leaves, stems and roots, while at harvest maturity stage, the plants were separated into aerial biomass (leaves + stems) and roots, due to their senescence conditions. The plant materials were dried in a hot-air oven at 45 °C for 5 days, ground with an electrical grinder, sieved through a 1 mm sieve, and kept in a dry and dark bag at 10 °C for future use. Each different plant material (leaves, stems, roots and aerial biomass) was soaked in distilled water for 24 h at 24 °C in laboratory to give concentration of 25 g of dry tissue per 100 ml of water (25% w/v). After soaking, the aqueous solutions were filtered through a 4-layer of cheesecloth to remove the fibre debris and then the aqueous extracts were filtered again through filter paper and used as stock extracts in the Petri dish bioassays.

Total polyphenols (TP) content

The Folin–Ciocalteu method (Singleton and Rossi 1965) was applied to determine the total polyphenols (TP) content of coriander extracts. In total, Folin–Ciocalteu reagent and 1.6 ml of a 7.5% Na₂CO₃ solution were added to 0.4 ml of extract. The obtained solution was incubated for two hours at room temperature. The absorbance was measured at 765 nm. The content of TP was expressed as mg of GA equivalent (GAE) per ml of extract (mg GAE ml⁻¹).

Phenolic acids

Phenolic Acids (PAs) were analysed using an UHPLC system consisting coupled with an UV–vis detector (Bravi et al. 2021). Briefly, the separation was carried out using a SunShell C18 column (ChromaNik Technologies Inc., Osaka 552–0001 Japan, 50 mm × 2.1 mm ID) at 25 °C and a flow rate of 0.4 ml/min. Mobile phase A was 0.1 M citric acid and 0.2 M sodium hydrogen phosphate (85/15; v/v), and mobile phase B was phase A, methanol and acetonitrile (30/20/50, v/v/v). The chromatographic separation was achieved using the following

elution gradient: mobile phase A 90% (0 min), 100% (2 min), 70% (8 min), 50% (10 min), 20% (12 min), 90% (12.5 min). The wavelengths of the three channels used for the detection were 254, 278, and 324 nm. The external standard method was used for the calibration. The calibration curve for each phenolic compound was plotted using UV detection close to the maximum UV absorption for a given substance.

Flavonoids content

The contents of total flavonoids (F) were calculated by subtracting from the total polyphenols content (TP) the total non-flavonoid content (NF), measured following the method of Falcinelli et al. (2017). Briefly, non-flavonoids were extracted by mixing an aliquot of phenolic extract with hydrochloric acid 1:4 (v/v) and formaldehyde. The mixture was kept at room temperature for 24 h and centrifuged at 1000 g for 15 min. As described above for TP, aliquot (0.4 ml) of extract was mixed with Folin–Ciocalteu reagent sodium carbonate and the absorbance was read after two hours.

Petri dishes bioassays

Petri dish bioassays were carried out according to the methodology already showed by Pannacci et al. (2015; 2013). Seeds of white mustard (*S. alba*, cv. Max), wheat (*T. aestivum*, cv. Bilancia), Italian ryegrass (*L. multiflorum*, cv. Devis) and redroot pigweed (*A. retroflexus*) were pre-sterilized with 2% sodium hypochlorite for 5 min. and washed with distilled water. Fifty seeds of each species were evenly placed on filter paper in sterilized separate 120-mm Petri dishes. Each stock extract was diluted with distilled water to prepare 0, 2.5, 5, 10, 17.5, 25% w/v concentrations, these were added at 7 ml per Petri dish. The treatments were replicated thrice according to a completely randomized design. All Petri dishes in bioassays were placed in a growth chamber at dark, with temperature of 20 °C. Germinated seeds were counted after 10 days in all species, and ten representative seedlings per Petri dish were chosen to determine the radicle and hypocotyl lengths in all species. Furthermore, in *S. alba* also fresh weight of seedlings was measured. Data on seed germination, radicle length, hypocotyl length and weight of seedlings were converted to percentage relative to untreated control (Abbott 1925).

Statistical analysis

Samples extracts were analysed in triplicate, and results are given as averages with standard deviation in parentheses, with some values that were under the limit of detection method. Bioassays data were subjected to nonlinear

regression analyses by using the log-logistic model proposed by Streibig et al. (1993):

$$Y = C + \frac{D - C}{1 + \exp\{b[\log(X) - \log(a)]\}} \quad (1)$$

where Y is the response (i.e. percentage of seed germination, radicle length, hypocotyl length and weight of seedlings) of the test specie as a function of the extract concentration X, D is the upper asymptote (response of the untreated control), C is the lower asymptote (response at extremely high concentration), a is the concentration that give a response half way between upper and lower asymptotes and b is the slope around the inflection point.

In some cases, growth stimulation was observed at low concentration doses, hence, the following peaked model was used (Brain and Cousens 1989):

$$Y = C + \frac{D - C + fX}{1 + \exp\{b[\log(X) - \log(a)]\}} \quad (2)$$

where, f is the parameter for stimulation.

Fitted equations were used to calculate the extract solution concentration required to give 50% and 90% reduction of the control value in terms of seed germination, radicle or meso/hypocotyl length of seedlings, i.e. EC50 and EC90 (effective concentration) (Pestemer and Günther 1995). The assumption that dose–response curves could be fitted to the

data was assessed by an F-test for lack-of-fit comparing the residual sum of squares of an analysis of variance and the nonlinear regression (Ritz and Streibig 2005).

The models were fitted to the experimental data using the EXCEL® Add-in macro BIOASSAY97 (Onofri e Pannacci, 2014).

Results and discussion

Chemical compounds in the coriander extracts

The content of chemical compounds found in the different coriander aqueous extracts is reported in Table 1.

All chemical compounds (TP, NF, F and PA) at flowering stage showed the highest contents in leaves extract and were lower in stems and roots extracts (Table 1). In particular, flavonoids content was higher than non-flavonoids content, especially in leaves but also in stems and aerial biomass due to the high content of TP, as also found by others authors (Helle et al. 2004; Scandar et al. 2023). Among phenolic acids (PA), the 3,4,5-trihydroxybenzoic was the highest in leaves extract (20.4 µg ml⁻¹) but decreased until to about 1 µg ml⁻¹ in stems and roots; similarly, the content of 3,5-dihydroxybenzoic was high in the leaves but completely non-existing in stems and roots extracts (Table 1). 4- hydroxybenzoic, 3- hydroxybenzoic, vanillic and salicylic

Table 1 Total polyphenols (TP), non-flavonoids (NF), flavonoids content (F) and phenolic acids (PA) profile of different coriander extracts at the concentration of 25% w/v (standard deviation values are in parentheses)

Chemical compounds	Extracts at flowering								Extracts at harvest maturity			
	Leaves		Stems		Roots		Aerial biomass (leaves + stems)		Aerial biomass		Roots	
TP (mg GAE ml ⁻¹)	2.95	(0.36)	0.58	(0.01)	0.21	(0.01)	0.73	(0.04)	0.57	(0.01)	0.27	(0.01)
NF (mg GAE ml ⁻¹)	0.82	(0.03)	0.24	(0.01)	0.09	(0.00)	0.22	(0.01)	0.22	(0.01)	0.09	(0.00)
F (mg GAE ml ⁻¹)	2.13	(0.39)	0.34	(0.01)	0.10	(0.00)	0.51	(0.06)	0.34	(0.01)	0.18	(0.01)
PA (µg ml ⁻¹)												
3,4,5-trihydroxybenzoic	20.36	(0.12)	0.87	(0.01)	1.15	(0.10)	5.28	(0.01)	2.01	(0.09)	2.71	(0.03)
3,5-dihydroxybenzoic	14.55	(0.33)	≤0.051	–	≤0.051	–	2.08	(0.07)	≤0.051	–	≤0.051	–
2,5-dihydroxybenzoic	0.85	(0.04)	4.06	(0.01)	3.52	(0.04)	1.06	(0.01)	0.40	(0.03)	0.42	(0.01)
4- hydroxybenzoic	10.58	(0.10)	4.15	(0.09)	2.08	(0.03)	5.81	(0.06)	2.17	(0.10)	1.02	(0.03)
3- hydroxybenzoic	8.62	(0.12)	5.51	(0.18)	2.53	(0.19)	6.86	(0.16)	3.01	(0.01)	0.57	(0.03)
Vanillic	15.09	(0.18)	6.81	(0.13)	8.77	(0.04)	8.11	(0.16)	4.49	(0.01)	5.04	(0.09)
Homovanillic	0.55	(0.01)	1.89	(0.03)	1.74	(0.21)	0.75	(0.03)	1.51	(0.01)	0.91	(0.03)
Syringic	0.67	(0.01)	3.38	(0.03)	2.44	(0.03)	2.72	(0.04)	1.93	(0.03)	1.47	(0.03)
p-coumaric	3.70	(0.19)	1.59	(0.04)	0.57	(0.01)	1.32	(0.10)	0.91	(0.04)	0.67	(0.06)
Salicylic	18.55	(0.09)	3.35	(0.22)	9.01	(0.10)	18.19	(0.10)	5.04	(0.24)	3.50	(0.04)
Ferulic	2.83	(0.07)	0.30	(0.01)	1.99	(0.07)	≤0.124	–	≤0.124	–	0.31	(0.01)
m-coumaric	≤0.199	–	0.34	(0.01)	≤0.199	–	≤0.199	–	≤0.199	–	≤0.199	–
Sinapic	1.57	(0.03)	≤0.153	–	0.88	(0.01)	0.25	(0.03)	0.27	(0.01)	0.58	(0.03)
o-coumaric	0.37	(0.03)	0.36	(0.03)	0.48	(0.04)	≤0.086	–	≤0.086	–	≤0.086	–

acids were the most abundant compounds in each extract, whereas 2,5-dihydroxybenzoic and syringic were higher in stems and roots extracts than in leaves extract (Table 1). Based on these results, therefore, the ranking among different extracts based on their chemical compounds content was: leaves extract > stems extract > roots extract (Table 1). At harvest maturity all the chemical compounds in the extracts decreased those found in the flowering stage, as it can be observed compared the values of chemical compounds for roots and aerial biomass extracts between the two growth stages (Table 1). These results were in accordance with those obtained by Nurzynska-Wierdak (2013) that found as the percentage of essential oil components varied with plant development: the herb collected at the initial stage of flowering had higher concentrations of essential oil components than the herb harvested from regrowing shoots.

Allelopathic activity of leaves, stems and roots aqueous extracts of coriander at two different growth stages on *S. alba*

The coriander plants sampled at flowering stage showed the following humidity values of the different parts: leaves (76.1%); stems (79.9%); roots (78.3%). Furthermore, their percentage distribution on the weight of the whole plant was as follows: leaves (17.8%); stems (73.4%); roots (8.8%). The coriander plants sampled at harvest maturity stage showed the following humidity values of the different parts: aerial biomass (12.7%); roots (14.7%). These values showed a prevalence of the stems over the other parts (leaves and roots), in the external plant structures at the flowering stage, while the humidity of the plant was reduced to lower values at the harvest maturity stage, due to plant senescence that allows the mechanical harvest of seeds.

In the bioassay with *S. alba*, leaves, stems, roots and aerial biomass aqueous extracts of coriander at the two different growth stages inhibited seed germination, radicle length, hypocotyl length and weight of seedlings in this test species (Figs. 1 and 2). Dose–response curves showed as the degree of inhibition increased with the extract concentration, according to the log-logistic model (Eq. 1), although, in some cases, data were well adapted to peaked model (Eq. 2). The EC₅₀ and EC₉₀ values were always well estimated from the dose–response curves, except, in some cases, because outside to the range of tested extract concentrations (Table 2).

At flowering stage, leaves extract showed higher allelopathic effects than stems and roots extracts, inhibiting more severely seed germination and seedling growth of the test species (Fig. 1). In particular, EC values of leaves extract were always lower than those of stems and roots extract, showing to be able to reduce of 50% all the parameters of

test species, with a concentration ranging from 3% to 7.7% w/v (Table 2). Similarly, Iqbal et al. (2020) found that seeds of coriander powder extract at 1 to 5% w/v significantly affected the growth characteristics (root, shoot, seedling length and dry mass) of mung bean [*Vigna radiata* (L.) R. Wilczek]. Stem extracts always tended to cause to lower EC values than root extracts being significantly different in some cases (Table 2). Based on these results, therefore, the ranking among different extracts based on their allelopathic effects to inhibit seed germination and seedling growth of *S. alba* was: leaves extract > stems extract > roots extract (Fig. 1; Table 2). This ranking is equal to the chemical compound content of the extracts (Table 1), meaning that TP, F and PA were involved in the allelopathic activity of coriander, being higher in leaves extract than in stems and roots extracts (Table 1). Not by chance, phenolic compounds, including phenolic acids and flavonoids, are among the most studied groups of allelopathic activity and their effects are generally due to a complex phenomenon that involve more compounds with antagonist or synergic effect and rarely a single compound (Qasem 1995; Hoang et al., 2021). However, based on the EC values of the extracts at flowering stage, higher in leaves extract and lower in stem and root extract, it seems to be plausible that, among PA compounds, those with a high content in leaves and low in stems and roots, could be involved in the allelopathic effects against *S. alba*; i.e. 4- hydroxybenzoic, 3- hydroxybenzoic, vanillic, p-coumaric and salicylic acid (Table 1). From a practical perspective, phenolic allelochemicals present promising alternatives to synthetic herbicides. Their natural origin, rapid biodegradation, and minimal residual impact on the environment make them ideal candidates for sustainable weed management (Mushtaq and Fauconnier 2024). Furthermore, the highest allelopathic activity in coriander leaves with respect to stems and roots was observed in other species, such as *Helianthus annuus* L. (Pannacci et al. 2013; Ashrafi et al. 2008), *Artemisia vulgaris* L. (Pannacci et al. 2015; Barney et al. 2005), and *Cannabis sativa* L. (Patanè et al. 2023). Allelopathic activity of coriander against seed germination and seedling growth of weeds and crops was observed by other authors (Iqbal et al. 2015; Ravlić et al. 2013). At harvest maturity stage of coriander, allelopathic inhibitory effects of the water extracts of the aerial biomass were higher than those of the root extract, confirming the results obtained at flowering stage (Fig. 2). Furthermore, the inhibitory effects were more pronounced on seedling growth (hypocotyl length, radicle length and seedling weight) than on seed germination (Fig. 2; Table 2). The allelopathic activity of coriander at harvest maturity decreased with respect to that of coriander at flowering stage, otherwise the biostimulation effects, due to the hormetic effect, increased, especially for hypocotyl length (Figs. 1 and 2; Table 1). In fact, in the dose–response curves, the values of stimulation

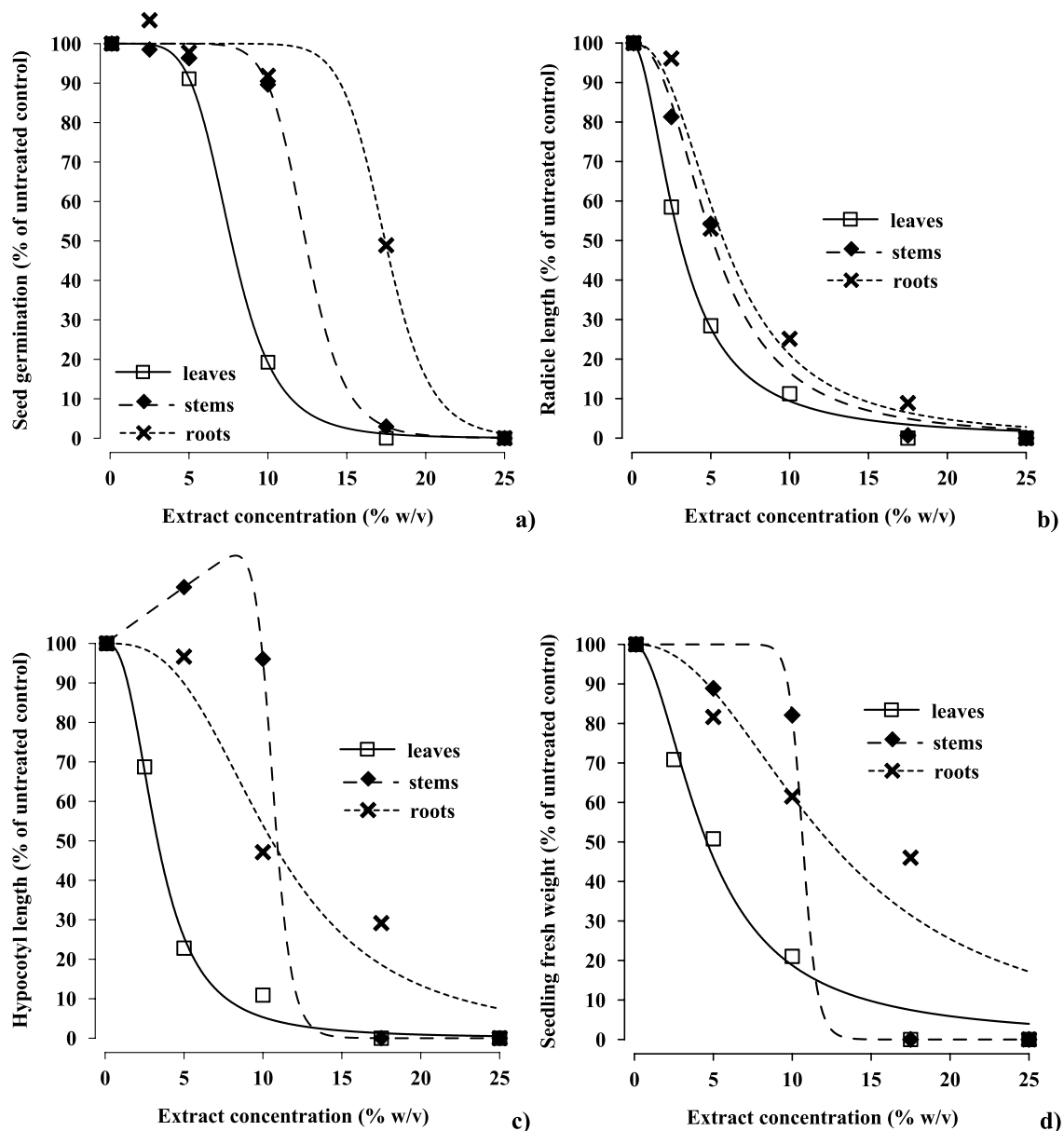


Fig. 1 Effects of leaves, stems and roots aqueous extracts of coriander at flowering stage on seed germination (graphic a), radicle length (graphic b), hypocotyl length (graphic c) and seedling weight

(graphic d) of *Sinapis alba* L. (test specie). Symbols show observed data, and lines show fitted curves according to model 1 and 2

parameter f were always statistically significant ($P < 0.05$) (data not shown) and EC values increased out the range of the investigated aqueous extracts concentrations ($> 25\%$ w/v) (Table 2). This stimulation phenomenon has been observed in plants with allelopathic extracts applied at low concentrations and their applications as potential biostimulants, from an agricultural point of view, have been investigated (Godlewska et al. 2021; Pannacci et al. 2022). In fact, the aqueous extracts of coriander at harvest maturity stage were characterized by lower allelochemicals content than those at flowering stage (Table 1), allowing to stimulate growth

of hypocotyl, radicle and weight of *S. alba* seedlings when applied at low concentration (5% w/v). Also in this case, 4- hydroxybenzoic, 3- hydroxybenzoic, vanillic, p-coumaric and salicylic acid could be the allelochemicals involved in the effects because their contents decrease in the extracts at harvest maturity with respect to extracts a flowering stage (Table 1). These results are supported by Telci et al. (2006) that found as, in coriander, essential oil contents of premature fruits were higher than that of ripened fruits. Similar findings in the variation of essential oil contents at different growth stages of coriander were reported by Al-Khayri

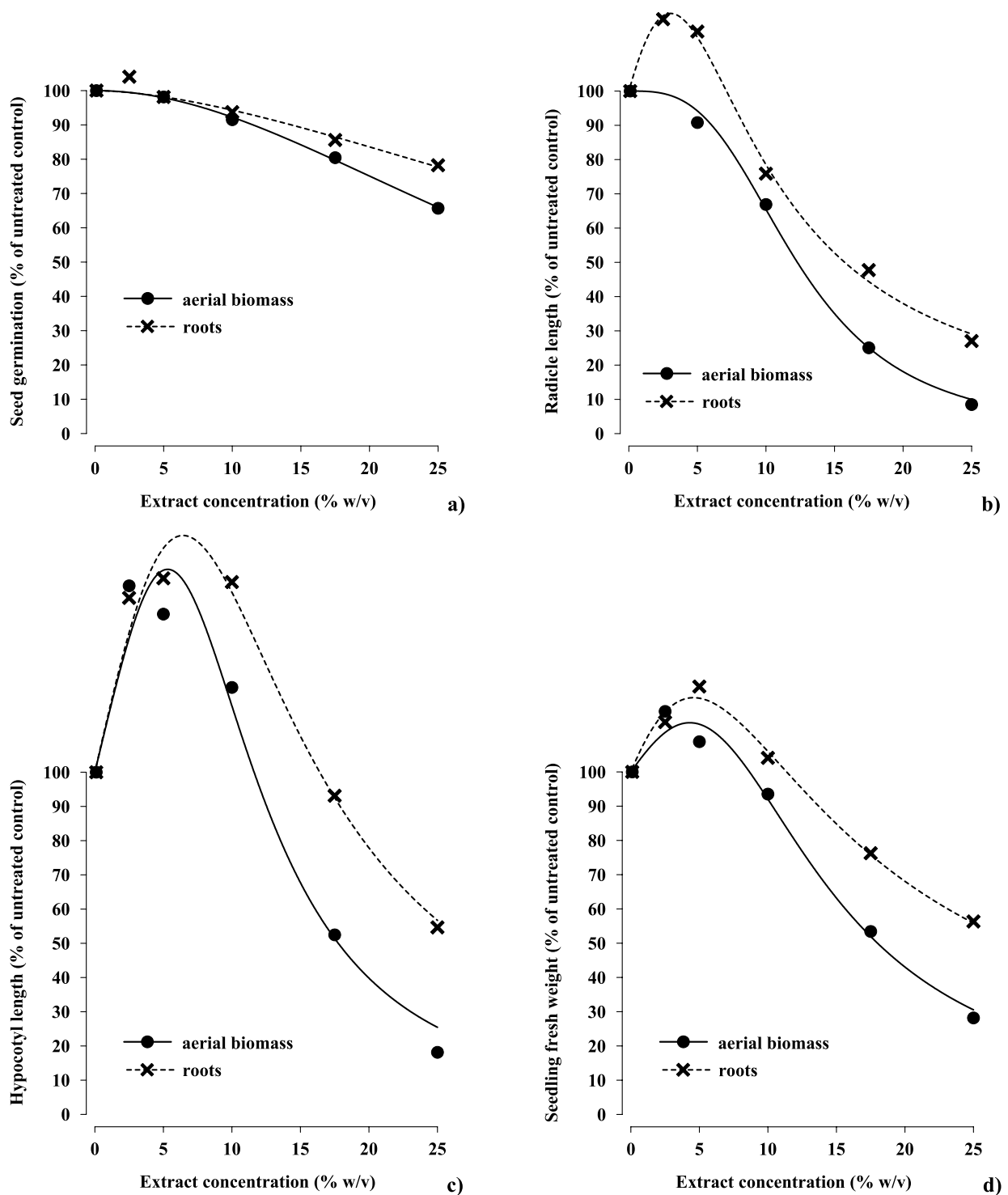


Fig. 2 Effects of aerial biomass and roots aqueous extracts of coriander at harvest maturity stage on seed germination (graphic a), radicle length (graphic b), hypocotyl length (graphic c) and seedling weight

(graphic d) of *Sinapis alba* L. (test specie). Symbols show observed data, and lines show fitted curves according to model 1 and 2

et al. (2023). Furthermore, it is well documented that concentrations of allelochemicals in living plants decrease with the age of the plant (An et al. 2003). For these reasons, the

higher allelopathic activity of the aerial parts (leaves and stems) of coriander at flowering stage, could suggest its potential harvesting as a whole plant at this stage, with the

Table 2 EC₅₀ and EC₉₀ values (% w/v) of leaves, stems, roots and aerial biomass aqueous extract of coriander at flowering and harvest maturity stages, on germination, radicle length, hypocotyl length and seedling weight of *S. alba*, extrapolated from dose–response curves showed in Figs. 1 and 2 (standard errors or confidence intervals are in parentheses)

Growth stage	Extract	Seed germination		Radicle length		Hypocotyl length		Seedling weight	
		EC ₅₀	EC ₉₀	EC ₅₀	EC ₉₀	EC ₅₀	EC ₉₀	EC ₅₀	EC ₉₀
Flowering	leaves	7.7 (0.21)	11.5 (0.40)	3.0 (0.12)	9.6 (0.78)	3.3 (0.14)	7.7 (0.72)	4.6 (0.39)	14.7 (2.68)
	stems	12.4 (0.36)	15.4 (0.82)	5.1 (0.30)	12.7 (2.04)	11.1 (1.33)	12.8 (2.03)	10.8 (1.02)	11.6 (1.04)
	roots	17.4 (0.19)	20.8 (2.26)	5.8 (0.39)	14.4 (2.04)	10.6 (1.09)	22.4 (4.76)	12.3 (1.01)	> 25
Harvest maturity	aerial biomass	> 25	> 25	12.3 (0.29)	25.0 (1.23)	17.8 (19.5–9.1)	> 25	18.0 (18.5–9.3)	> 25
	roots	> 25	> 25	15.2 (0.88)	> 25	> 25	> 25	> 25	> 25

aim of obtaining aqueous extracts to be applied directly in the field as pre-emergence bioherbicides. This utilization has already been demonstrated by some authors with coriander (Dhima et al. 2009) and with other species (Pannacci et al. 2015). In this regard, harnessing the allelopathic activity of coriander could find a valuable application in managing weed infestations in vegetable and minor crops, where the availability of herbicides is very limited (Pannacci et al. 2017). In particular, the choice of transplanted vegetable crops instead of direct-seeded ones, which can follow coriander in crop rotations, such as fennel, radish, an cabbage could help to reduce any potential negative allelopathic effects on crop germination. This is based on studies by Kruse et al. (2000), which have shown that plants are more sensitive to allelopathic substances at seed stage, whereas they become less sensitive if these substances are present in the rhizosphere during subsequent stages of development. Furthermore, the results obtained suggest that the use of coriander as a seed crop, harvested at full maturity, not only represents income for the farmer but also leaves crop residues (aerial and root parts) in the soil with allelopathic activity. These residues are potentially capable of inhibiting the germination and growth of weeds in subsequent crops. Dhima et al. (2009) found that coriander, incorporated into the soil as green manure before maize sowing, was able to reduce common lambsquarters (*C. albus*) plants emergence and their weight, without any effects on maize emergence and growth. However, in order to apply these finding in an IWMS, more knowledge is needed, especially about the effects in field application (Jabran et al. 2015). In the absence of data in this regard, it is important to note that in the agricultural company, from which the coriander biomass was taken for this experimentation, the crops used in succession to coriander, have consistently shown reduced weed presence, with evident benefits in terms of growth and yields (Bartocci, personal communication).

Allelopathic activity of aerial biomass (leaves + stems) aqueous extracts of coriander at flowering stage on *T. aestivum* and weeds

The aqueous extracts from aerial biomass (leaves + stems) of coriander at flowering stage inhibited the seed germination of *L. multiflorum* and *A. retroflusum*, but not that of *T. aestivum* (Figs. 3a and 4a, c). These results are in agreement with Pannacci et al. (2015) that found as the aqueous extracts from aerial biomass (leaves + stems) of mugwort (*A. vulgaris*) inhibited the seed germination of *L. multiflorum* but not that of *T. aestivum*. The aqueous extracts of aerial biomass of coriander, at 2% and 4% w/v

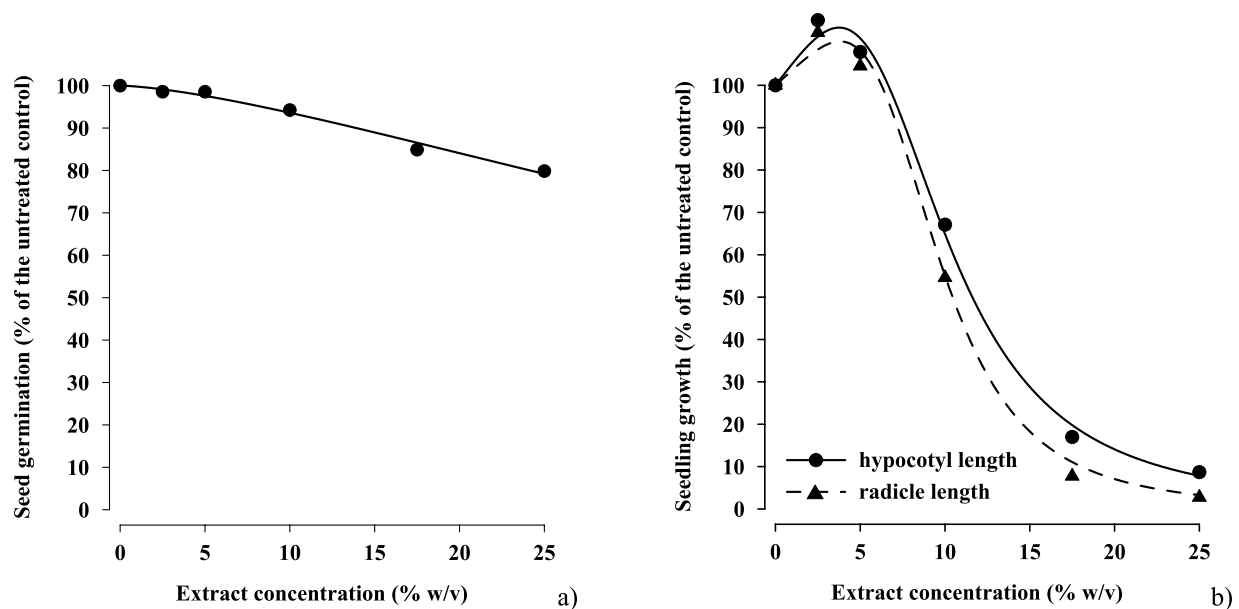


Fig. 3 Effects of aerial biomass (leaves+stems) aqueous extracts of coriander at flowering stage on seed germination (graphic a) and seedling growth (hypocotyl and radicle lengths, graphic b) of *Triti-*

cum aestivum L. Symbols show observed data, lines show fitted curves according to model 1 and 2

concentrations, inhibited the seed germination, root elongation and seedling weight of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] of 98%, without any effects on seed germination, root elongation and seedling weight of maize (Dhima et al. 2009). In particular, the inhibition of seed germination of weeds (*L. multiflorum* and *A. retroflexus*) was severe at the two highest extract concentrations (17.5%–25% w/v), whereas, at the lowest concentrations, seed germination of *A. retroflexus* was greatly stimulated (Fig. 4c), with a significant stimulation parameter value ($f = 28.5 \pm 0.82$, $P < 0.001$). Stimulation effect at the lowest extract concentrations was also observed on the hypocotyl length of *A. retroflexus* ($f = 27.8 \pm 4.2$, $P < 0.001$), whereas the radicle length was strongly inhibited (Fig. 4d; Table 3). *A. retroflexus* showed similar response when treated with aqueous extract of aerial biomass of mugwort (*A. vulgaris*), although in this case seed germination was severely inhibited and not stimulated by the lowest extract concentrations (Pannacci et al. 2020). Isik et al. (2016) using bioassays with aqueous extracts of aerial biomass of coriander at different concentration found that EC_{50} and EC_{90} against *C. album* were 1.8 and 36.9, 4.0 and 20.8, 3.1 and 3.1 for the inhibition of seed germination, radicle and hypocotyl length, respectively. These EC_{90} values were higher than those obtained in the present research on *L. multiflorum* and *A. retroflexus*, showing that coriander extract is less effective against *C. album* than against *L. multiflorum* and *A. retroflexus*.

Conclusions

The following conclusions can be drawn with the present results: i) at flowering stage, the leaves of *C. sativum* exhibit greater allelopathic activity compared to the stems and roots, with the following decreasing ranking: leaves > stems > roots; ii) the allelopathic activity of *C. sativum* tends to decrease as the phenological stage progresses, although it remains present even at the crop's maturity stage; iii) total polyphenols, flavonoids and phenolic acids were involved in the allelopathic activity of coriander; iv) aqueous extracts of aerial biomass of coriander at flowering stage could be used as a bioherbicide against the weeds *L. multiflorum* and *A. retroflexus*, without toxic effects against *T. aestivum*; v) *C. sativum* could be used as a “dead mulching”, an intercropping crop or be harvested as a whole plant at flowering stage to obtain aqueous extracts to be directly applied in the field as pre-emergence bioherbicides in organic farming. The use of coriander as a seed crop, besides representing an income for the farmer, leaves crop residues with allelopathic activity in the soil, potentially able to inhibit the germination and growth of weeds in successive crops. Based on practical experience, crops sowed in succession to coriander benefit from it, both in terms of reduced weed presence and in terms of growth and yields.

This research has provided interesting scientific insights into the allelopathic activity of *C. sativum* and its potential use in weed management. However, other aspects need to be further investigated, as: i) to expand knowledge on the

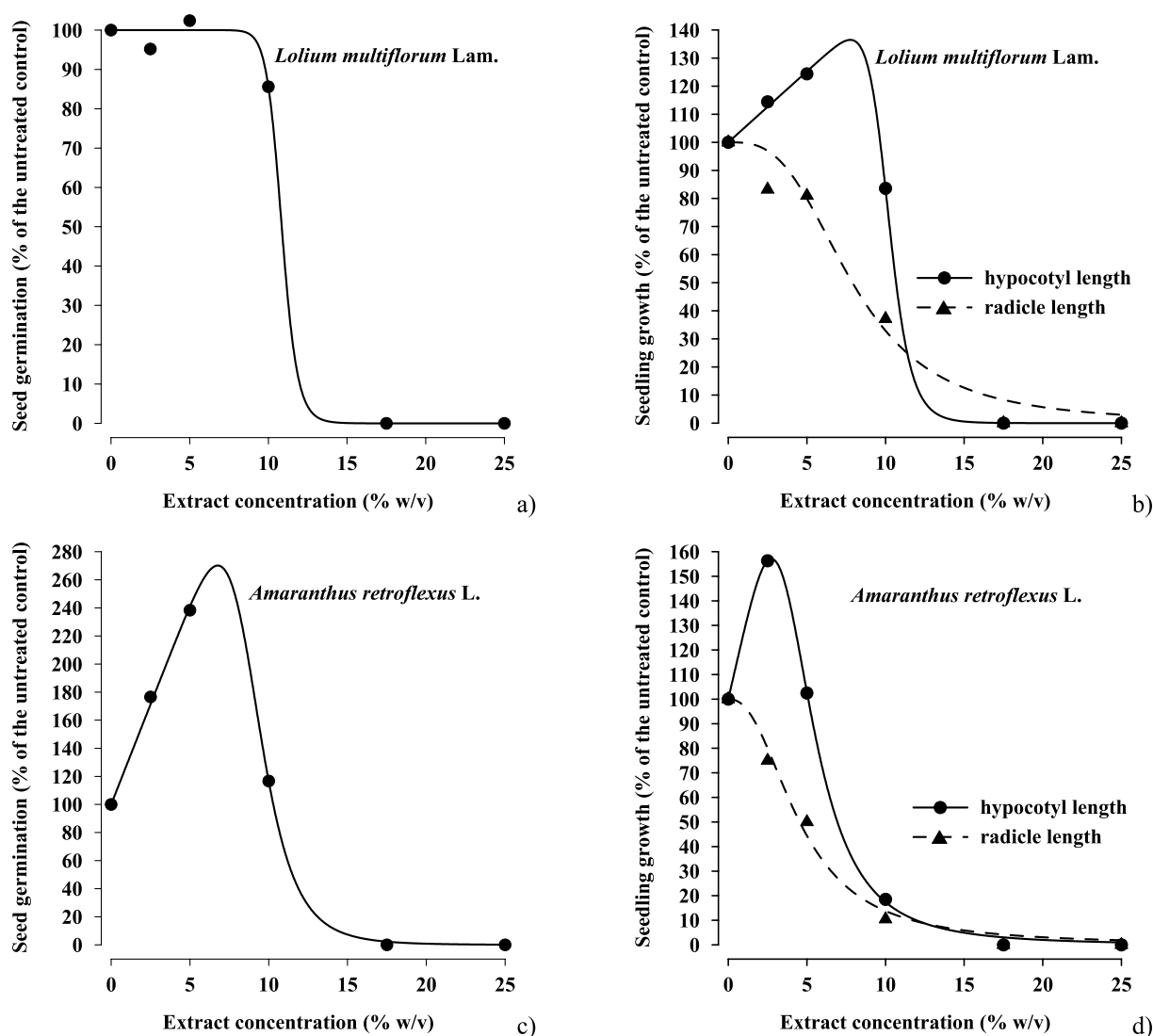


Fig. 4 Effects of aerial biomass (leaves+stems) aqueous extracts of coriander at flowering stage on seed germination (graphic a and c) and seedling growth (hypocotyl and radicle lengths, graphic b and d)

of *Lolium multiflorum* Lam. and *Amaranthus retroflexus* L. Symbols show observed data, and lines show fitted curves according to model 1 and 2

Table 3 EC₅₀ and EC₉₀ values (% w/v) of aerial biomass (leaves+stems) aqueous extract of coriander at flowering stage, on seed germination and seedling growth (radicle and hypocotyl length)

Specie	Seed germination		Radicle length				Hypocotyl length			
	EC ₅₀	EC ₉₀	EC ₅₀		EC ₉₀		EC ₅₀		EC ₉₀	
<i>Triticum aestivum</i> L	> 25	> 25	10.3	(0.40)	17.7	(2.09)	11.6	(0.67)	22.9	(2.30)
<i>Lolium multiflorum</i> Lam	10.8	(0.51)	12.0	(0.98)	7.9	(0.68)	16.4	(2.70)	10.7	(0.74)
<i>Amaranthus retroflexus</i> L	11.5	(1.21)	14.4	(1.83)	4.5	(0.16)	11.7	(0.91)	6.9	(0.48)

effects of *C. sativum* aqueous extract on more potential successive crops and their associated weeds; ii) to investigate the bioavailability of the extract in the soil and iii) to study the effects of individual allelochemicals contained in the

extracts that are potentially responsible for the allelopathic phenomena, with the aim of using them as precursors for the synthesis of herbicides with new modes of action.

Author contributions Conceptualization: [Euro Pannacci]; Methodology: [Euro Pannacci], [Giulia Contini]; Data curation: [Euro Pannacci], [Giulia Contini]; Formal analysis and investigation: [Euro Pannacci], [Giulia Contini], [Elisabetta Bravi]; Writing—original draft preparation: [Euro Pannacci], [Vittorio Monni]; Writing—review and editing: [Euro Pannacci], [Vittorio Monni], [Francesco Tei]; Supervision: [Euro Pannacci], [Francesco Tei].

Funding Open access funding provided by Università degli Studi di Perugia within the CRUI-CARE Agreement.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

- Abbas T, Zahir ZA, Naveed M, Kremer RJ (2018) Limitations of existing weed control practices necessitate development of alternative techniques based on biological approaches. *Adv Agron* 147:239–280. <https://doi.org/10.1016/bs.agron.2017.10.005>
- Abbott WS (1925) A method of computing the effectiveness of an insecticide. *J Econ Entomol* 18:265–267. <https://doi.org/10.1093/jee/18.2.265a>
- Al-Khayri JM, Banadka A, Nandhini M, Nagella P, Al-Mssallem MQ, Alessa FM (2023) Essential oil from coriandrum sativum: a review on its phytochemistry and biological activity. *Molecules* 28:696. <https://doi.org/10.3390/molecules28020696>
- An M, Liu DL, Johnson IR, Lovett J (2003) Mathematical modelling of allelopathy: II. The dynamics of allelochemicals from living plants in the environment. *Ecol Model* 161:53–66. [https://doi.org/10.1016/S0304-3800\(02\)00289-2](https://doi.org/10.1016/S0304-3800(02)00289-2)
- Ashrafi ZV, Sadeghi S, Mashhadi HR, Hassan AM (2008) Allelopathic effects of sunflower (*Helianthus annuus*) on germination and growth of wild barley (*Hordeum spontaneum*). *Int J Agric Technol* 4:219–229
- Barney JN, Anthony GH, Weston LA (2005) Isolation and characterization of allelopathic volatiles from mugwort (*Artemisia vulgaris*). *J Chem Ecol* 31:247–265. <https://doi.org/10.1007/s10886-005-1339-8>
- Bhowmik PC (2003) Challenges and opportunities in implementing allelopathy for natural weed management. *Crop Prot* 22:661–671. [https://doi.org/10.1016/S0261-2194\(02\)00242-9](https://doi.org/10.1016/S0261-2194(02)00242-9)
- Brain P, Cousens R (1989) An equation to describe dose responses where there is stimulation of growth at low dose. *Weed Res* 29:93–96. <https://doi.org/10.1111/j.1365-3180.1989.tb00845.x>
- Bravi E, Francesco GD, Sileoni V, Perretti G, Galgano F, Marconi O (2021) Brewing by-product upcycling potential: nutritionally valuable compounds and antioxidant activity evaluation. *Antioxidants* 10:165
- Dhima KV, Vasilakoglou IB, Gatsis TD, Panou-Philotheou E, Eleftherohorinos IG (2009) Effects of aromatic plants incorporated as green manure on weed and maize development. *Field Crops Res* 110:235–241. <https://doi.org/10.1016/j.fcr.2008.09.005>
- Dhima K, Vasilakoglou I, Garane V, Ritzoulis C, Lianopoulou V, Panou-Philotheou E (2010) Competitiveness and essential oil phytotoxicity of seven annual aromatic plants. *Weed Sci* 58:457–465
- Diederichsen A (1996) Coriander (*Coriandrum sativum* L.). Promoting the conservation and use of underutilized and neglected crops. Bioversity International. International Plant Genetic Resources Institute, Rome, Italy
- Falcinelli B, Marconi O, Maranghi S, Lutts S, Rosati A, Famiani F, Benincasa P (2017) Effect of genotype on the sprouting of pomegranate (*Punica granatum* L.) seeds as a source of phenolic compounds from juice industry by-products. *Plant Foods Hum Nutr* 72:432–438
- Godlewska K, Ronga D, Michalak I (2021) Plant extracts - importance in sustainable agriculture. *Ital J Agron*. <https://doi.org/10.4081/ija.2021.1851>
- Hammer K (2004) Resolving the challenge posed by agrobiodiversity and plant genetic resources: an attempt. Kassel University Press, Germany
- Heap I (2024) The International Survey of Herbicide Resistant Weeds. Online. <https://www.weedscience.org/Home.aspx> Accessed 1 June 2024
- Helle W, Samuelsen AB, Malterud KE (2004) Antioxidant activity in extracts from coriander. *Food Chem* 88:293–297. <https://doi.org/10.1016/j.foodchem.2004.01.047>
- Hoang Anh L, Van Quan N, Tuan Nghia L, Dang Xuan T (2021) Phenolic allelochemicals: achievements, limitations, and prospective approaches in weed management. *Weed Biol Manage* 21:37–67
- Iqbal MZ, Ahmed L, Shafiq F, Athar M (2015) Allelopathic effects of red pepper and coriander on early seedling growth of wheat. *Ad Environ Res* 4:1–15. <https://doi.org/10.12989/aer.2015.4.1.001>
- Iqbal MZ, Ahmed L, Shafiq F, Kabir M, Farooqi ZUR (2020) Seed germination and early seedling growth performance of (*Vigna radiata* L. Wilczek) in response to aqueous powder extract of *Capsicum annum* L. and *Coriandrum sativum* L. *Biosci Res* 17:948–956
- Isik D, Mennan H, Cam M, Tursun N, Arslan M (2016) Allelopathic potential of some essential oil bearing plant extracts on Common Lambsquarters (*Chenopodium album* L.). *Rev* 67:455–459
- Jabran K, Mahajan G, Sardana V, Chauhan BS (2015) Allelopathy for weed control in agricultural systems. *Crop Prot* 72:57–65. <https://doi.org/10.1016/j.cropro.2015.03.004>
- Jamil M, Cheema ZA, Mushtaq MN, Farooq M, Cheema MA (2009) Alternative control of wild oat and canary grass in wheat fields by allelopathic plant water extracts. *Agron Sustain Dev* 29:475–482. <https://doi.org/10.1051/agro/2009007>
- Kruidhof HM, van Dam NM, Ritz C, Lotz APL, Kropff MJ, Bastiaans L (2014) Mechanical wounding under field conditions: A potential tool to increase the allelopathic inhibitory effect of cover crops on weeds? *Europ J Agronomy* 52:229–236. <https://doi.org/10.1016/j.eja.2013.09.003>
- Kruse M, Strandberg M, Strandberg B (2000) Ecological effects of allelopathic plants -a review. *National Environ Res Inst Silkeborg, Denmark – NERI Tech Rep* 315:66
- Li ZH, Wang Q, Ruan X, Pan CD, Jiang DA (2010) Phenolics and plant allelopathy. *Molecules* 15:8933–8952
- Mallik AU (2008) Allelopathy: Advances, Challenges and Opportunities. In: Zeng RS, Mallik AU, Luo SM (eds) *Allelopathy in Sustainable Agriculture and Forestry*. Springer, New York, pp 25–38
- Maurya P, Dwivedi N, Majeed A et al (2024) Allelopathic weed management in wheat (*Triticum aestivum* L.) through essential oil

- emulsions and aqueous botanical extracts-based novel bioherbicides. *J Plant Dis Prot* 131:445–458. <https://doi.org/10.1007/s41348-024-00870-9>
- Mushtaq W, Fauconnier ML (2024) Phenolic profiling unravelling allelopathic encounters in agroecology. *Plant Stress* 13:100523
- Nelson AG, Pswarayi A, Quideau S, Frick B, Spaner D (2012) Yield and weed suppression of crop mixtures in organic and conventional systems of the Western Canadian Prairie. *Agron J* 104:756–762. <https://doi.org/10.2134/agronj2011.0374>
- Nurzyska-Wierdak R (2013) Essential oil composition of the coriander (*Coriandrum sativum* L.) herb depending on the development stage. *Acta Agrobot* 66:53–60. <https://doi.org/10.5586/aa.2013.006>
- Onofri A, Pannacci E (2014) Spreadsheet tools for biometry classes in crop science programmes. *Commun Biom Crop Sci* 9:3–13
- Pannacci E, Pettorossi D, Tei F (2013) Phytotoxic effects of aqueous extracts of sunflower on seed germination and growth of *Sinapis alba* L., *Triticum aestivum* L. and *Lolium multiflorum* Lam. *Allelopathy J* 32:23–36
- Pannacci E, Pettorossi D, Regni L, Tei F (2015) Allelopathic potential of mugwort (*Artemisia vulgaris* L.) to control the Italian ryegrass (*Lolium multiflorum* Lam.) in winter wheat. *Allelopathy J* 36:257–272
- Pannacci E, Lattanzi B, Tei F (2017) Non-chemical weed management strategies in minor crops: A review. *Crop Prot* 96:44–58. <https://doi.org/10.1016/j.cropro.2017.01.012>
- Pannacci E, Masi M, Farneselli M, Tei F (2020) Evaluation of mugwort (*Artemisia vulgaris* L.) aqueous extract as a potential bioherbicide to control *Amaranthus Retroflexus* L. in maize. *Agriculture* 10:642. <https://doi.org/10.3390/agriculture10120642>
- Pannacci E, Baratta S, Falcinelli B, Farneselli M, Tei F (2022) Mugwort (*Artemisia vulgaris* L.) Aqueous Extract: Hormesis and Biostimulant Activity for Seed Germination and Seedling Growth in Vegetable Crops. *Agriculture* 12:1329. <https://doi.org/10.3390/agriculture12091329>
- Patanè C, Alessandra P, Salvatore LC, Giorgio T (2023) Allelopathic Effects of *Cannabis sativa* L. Aqueous Leaf Extracts on Seed Germination and Seedling Growth in Durum Wheat and Barley. *Agron* 13:454
- Pestemer W, Günther P (1995) Growth Inhibition of Plants as a Bioassay for Herbicide Analysis. In: Börner H, Martin D, Sjut V, Stetter J (eds) Stan HJ, Ebing iR W. *Analysis of Pesticides in Ground and Surface Water I. Chemistry of Plant Protection*, Springer, Berlin, Heidelberg
- Pheng S, Olofsdotter M, Jahn G, Steve Adkins S (2010) Use of phytotoxic rice crop residues for weed management. *Weed Biol Manag* 10:176–184. <https://doi.org/10.1111/j.1445-6664.2010.00382.x>
- Puig CG, Revilla P, Barreal ME, Reigosa MJ, Pedrol N (2019) On the suitability of *Eucalyptus globulus* green manure for field weed control. *Crop Prot* 121:57–65. <https://doi.org/10.1016/j.cropro.2019.03.016>
- Qasem JR (1995) Allelopathic effects of *A. retroflexus* and *Chenopodium murale* on vegetable crops. *Allelopathy J* 2:49–66
- Ravlić M, Baličević R, Pejić T, Pećar N (2013) Allelopathic effect of cogermination of some aromatic plants and weed seeds. In: *Proceedings and abstracts of the 6th International Scientific/Professional Conference Agriculture in Nature and Environment Protection*. Glas Slavonije, Osijek
- Rice EL (1984) *Allelopathy*. Academic Press, New York
- Ritz C, Streibig JC (2005) Bioassay analysis using R. *J Stat Softw* 12:1–22. <https://doi.org/10.18637/jss.v012.i05>
- Scandar S, Zadra C, Marcotullio MC (2023) Coriander (*Coriandrum sativum*) polyphenols and their nutraceutical value against obesity and metabolic syndrome. *Molecules* 28:4187. <https://doi.org/10.3390/molecules28104187>
- Scognamiglio M, D'Abrosca B, Esposito A, Pacifico S, Monaco P, Fiorentino A (2013) Plant growth inhibitors: allelopathic role or phytotoxic effects? Focus on Mediterranean biomes. *Phytochem Rev* 12:803–830. <https://doi.org/10.1007/s11101-013-9281-9>
- Seidemann J (2005) *World spice plants: economic, usage, botany, taxonomy*. Springer-Verlag, Berlin, Heidelberg
- Singleton VL, Rossi JA (1965) Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *Am J Enol Viticult* 16:144–158
- Soltys D, Krasuska U, Bogatek R, Gniazdowska A (2013) Allelochemicals as bioherbicides – Present and perspectives. In: Price AJ, Kelton JA (eds) *Herbicides – Current Research and Case Studies in Use*. IntechOpen Limited, London, UK
- Streibig JC, Rudemo M, Jensen JE (1993) Dose-response curves and statistical models. In: *Herbicide Bioassay* CRC (ed) Streibig JC, Kudsk P. Press, Boca Raton, FL, pp 29–55
- Telci I, Bayram E, Avci B (2006) Changes in yields, essential oil and linalool contents of coriander sativum varieties (var. *vulgare* Alef. and var. *microcarpum* DC.) harvested at different development stages. *Europ J Hort Sci* 71:267–271
- Weston LA, Inderjit, (2007) Allelopathy: A potential tool in the development of strategies for biorational weed management. In: Upadhyaya MK, Blackshaw RE (eds) *Non-Chemical Weed Management – Principles. Concepts and Technology*, CABI Press, Oxfordshire, UK, pp 65–76
- Zanin G, Ferrero A, Sattin M (2011) La gestione integrata delle malerbe: un approccio sostenibile per il contenimento delle perdite di produzione e la salvaguardia dell'ambiente. *Ital J Agron* 6(s2):e6. <https://doi.org/10.4081/ija.2011.6.s2.e6>
- Zanin G, Tei F, Sartori L, Peruzzi A (2024) *Gestire le malerbe in agricoltura biologica*. Edagricole, Milano, Italy

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