



Assessing the Biostimulant Effects and Antimicrobial Activity of *Lavandula Angustifolia* Essential Oil

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Abstract

Biostimulation is a well-known method for enhancing plant growth. Several natural and artificial compounds have demonstrated efficacy in promoting plant growth and development by initiating specific physiological processes. The main objective of this research was to evaluate the antimicrobial activity and the biostimulant effect of *Lavandula angustifolia* essential oil on radish, which was selected as representative vegetable crop species. The chemical composition of the lavender essential oil (LEO) was characterized and used for antimicrobial assays on 6 microorganisms at different concentrations (2.0, 4.0 and 8.0%) and biostimulant tests (0.5, 1.0, 2.0 and 4.0%). LEO biostimulant effect was tested on two independent radish cycles performed in a Mediterranean greenhouse. LEO was mainly constituted by oxygenated monoterpenes including Linalool (36.81%) and Linalyl acetate (41.0%) and, in minor concentration, by other monoterpenes such as Limonene, Camphor, Endo-Borneol, Eucalyptol and β -Mircene 1.49%. The antimicrobial activity of LEO showed an inhibition index that increased proportionally to LEO concentration. *Staphylococcus aureus* showed the highest growth inhibition (about 89%) at 8.0% of LEO. All biometric and biomass parameters (plant height, leaf length, average leaf area, aerial and radish fresh weight) increased in both cycles with a LEO concentration till 4.0% ($p < 0.05$). Chlorophyll index, radish macro and micronutrient content did not differ significantly in both cycles based on the LEO content. The advantages of LEO as biostimulant can be promising in enhancing growth and yield of radish under the maximum dosage of 2.0%, while higher concentrations ($\geq 4.0\%$) caused phytotoxic effects. Further investigations could be conducted applying multiple low-dose foliar concentrations in other horticultural crops, to assess the potential application of LEO as natural herbicide for use in sustainable and organic farming.

Keywords Radish · Secondary metabolite · Physiology · Sustainable agriculture

1 Introduction

It is estimated that by 2050 there will be 9.7 billion people in the world with severe issues of food needs (Bashir et al. 2021). The potential increase of world population will induce a growth of food demand up to 70% (Buono 2021). Consequently, the higher resource uses efficiency of the

agricultural systems will represent one of the main goals in the future.

Over the years, an overuse of chemical fertilizers (1.9×10^{11} tons) has been deployed globally, especially under conventional agricultural systems (Wan et al. 2021). Although the use of fertilizers and pesticides has increased crop production, the fertilization practices have caused a loss of vegetable crop quality and several environmental issues (Chouhan et al. 2021). The agriculture intensification is highly dependent from the use of fertilisers, which highly contribute to air and groundwater pollution, as well as the deterioration of soil fertility. Furthermore, an increased susceptibility of productive species to biotic and abiotic stresses has been observed (Godlewka et al. 2021; Wan et al. 2021). Overall, the efforts of agriculture are focused on the use of innovative systems to improve plant growth and

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food production, reducing the use of fertilizers and stimulating plant metabolism through environmentally safe strategies (Bashir et al. 2021). To increase crop productivity and keep food safety as a priority, sustainable approaches for agricultural systems, such as the biostimulant application, have been proposed (Bulgari et al. 2015; Drobek et al. 2019; Rouphael and Colla 2020).

Biostimulants are a wide range of organic and inorganic substances with a positive effect on plant growth and development. The European Biostimulant Industry Council (EBIC) defines “biostimulants” as a group of compounds that improve the nutrient use efficiency and uptake of the plants, induce an increase of plant tolerance to biotic and abiotic stress, increase the yield and quality and are environmentally friendly (Bashir et al. 2021; Bell et al. 2022; Rehim et al. 2021). Samuels et al. (2022) classified them based on their origin: humic, aminoacid/nitrogen-containing, inorganic, chitosan/biopolymers, beneficial microbes, seaweed, and botanical extracts. Among all these compounds, the essential oils (EO) represent a class of natural compounds, isolated from aromatic species, that have been only partially explored for their biological activity on plants (Souri and Bakhtiarizade 2019). EOs are natural complex compounds responsible for the typical odor of aromatic plants, and they are mainly known for antioxidant, anti-inflammatory action, and other positive effects on human health (Bakkali et al. 2008; Jalali-Heravi et al. 2011). More recently, with the increasing interest in the application of natural substances in sustainable and organic cropping systems, the use of EOs as biostimulants has been proposed (Chrysargyris et al. 2020; Souri and Bakhtiarizade 2019). In the *Lamiaceae* family, lavender, rosemary, and sage EOs have been extensively applied as food preservatives, given their antimicrobial and antioxidant properties to extend the shelf life of food (Belcadi et al. 2024). In particular, *Lavandula angustifolia* is an aromatic plant suitable for growth in Mediterranean regions and has an EO composition rich in monoterpenes suggesting good antimicrobial and bioactive activity. However, there is no specific research in the literature on lavender essential oil (LEO) activity as direct biostimulant for plants, even if several studies demonstrated its protective effect against weeds and pathogens (Cavalieri and Caporali 2010; Lukošiušė et al. 2020). Under the European Regulation (EU) 2019/1009, essential oils obtained from plants are classified as plant extracts and can therefore be considered non-microbial plant biostimulants when used to enhance plant performance. In fact, in recent studies, compounds from lavender (aqueous extract) have been shown to significantly affect biomass, leaf-area, mineral content, and post-harvest quality of baby lettuce (Ritota et al. 2025). Although several EOs have been tested on horticultural crops with positive effects on morphological and

physiological traits (Şanlı et al. 2019; Costa et al., 2022; Pandey et al. 2022; Chrysargyris et al. 2020), LEO remains largely unexplored for its potential in stimulating plant growth and development.

Radish (*Raphanus sativus* L.) is a root vegetable crop belonging to the Brassicaceae family. It is cultivated mainly during the cold season and characterized by a short cycle. The demand for radish on the market has increased recently, as result of its nutritional value: vitamins A, B (complex) and C as well as iron, folic and nicotinic acid, potassium, dietary fiber, thiamine, riboflavin, are just some of the appreciated quality aspects of this root-crop specie (Araújo et al. 2020).

In the present study, a preliminary chemical characterization of the *L. angustifolia* EO was conducted to determine the concentration of EOs (mainly oxygenated monoterpenes) with antimicrobial activity and potential biostimulant effects. Subsequently, the research investigated the range of LEO concentrations determining a biostimulant or a phytotoxic effect on a representative horticultural crop such as radish, with the aim of assessing the response on plant growth, development, physiological parameters, macro and micronutrient content of the edible parts. The results highlighted the potential applications of LEO both as a biostimulant and bioherbicide and provide original information concerning the potential advantages of LEO-based biostimulants on radish morphophysiological parameters and their role towards a sustainable agriculture and food security.

2 Materials and methods

2.1 Essential Oil production, Extraction and Characterization

Lavender plants have been grown in a dynamic agrivoltaic system in the marginal rural area of San Severo, located in the Foggia Province of the Apulia region in Southern Italy (41° 34' 58.90" N; 15° 28' 33.85" E). This area represents a typical semi-arid environment characterized by a Mediterranean climate, specifically classified as “accentuated thermo-Mediterranean” (UNESCO 1963). The soil texture was identified as clay-loam (USDA 2017), offering an effective depth of over 120 cm and characterized as vertisol of alluvial origin. The soil composition included sand (38.6%), loam (22.4%), clay (39.0%), with nutrients such as total N (Kjeldahl method) at 2.7‰, assimilable P₂O₅ (Olsen method) at 58 ppm, exchangeable K₂O (Schollenberger method) at 539 ppm, Ca exchangeable at 2928 ppm, Mg exchangeable at 317 ppm, Na exchangeable at 34 ppm, C/N ratio at 5:2, electrical conductivity (EC) at 0.63 dS cm⁻¹, pH (in water) at 8.1, and organic matter (Walkley and Black method) at

2.5%. The soil was plowed to a depth of 40 cm and received two tillage operations with a disc harrow before transplanting the aromatic plants. Lavender plants were transplanted with a planting layout of 1.0×1.0 m (plant density 1 plant m^{-2}) in May 2022. Standard agronomic practices for aromatic crops (fertilization, drip irrigation, weed control, etc.) were employed.

Lavandula angustifolia L. Royal Purple were harvested on 29 June 2023 by hand in the balsamic phase. The freshly collected flowers of Lavender were used for hydrodistillation using a Clevenger-type apparatus (Clevenger 1928). For 2 h, 1 kg of fresh flowers was subjected to 2 hydrodistillations and extracted with 7 L of distilled water, following the European Pharmacopoeia (Council of Europe 2023). The hydrodistillation was conducted twice. At the end of the extraction, the accumulated EO floated on the aqueous phase (hydrolat). All the extracted material was transferred into a glass separating funnel for 4 h until total separation was achieved (EO/hydrolat). 20 mL of EO was produced (EO yield: 1.1%). EOs were stored in hermetically sealed dark glass containers and kept at 5–6 °C.

The LEO composition was determined through Gas Chromatography-Mass Spectrometry (GC-MS). In particular, one microliter of EO [Diluted samples 1:100 (v/v) in hexane] was analysed with an Agilent 7890B series gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) coupled with an Agilent 5977 A mass selective detector (MSD) and equipped with a HP-5MS capillary column (30 m $\times$ 0.25 mm ID, 0.5 μm film thickness, J&W Scientific Inc., Folsom, CA, USA). The carrier gas was helium at a flow rate of 1.25 mL/min. The injection was made in the splitless mode, and the injector temperature was 250 °C. The column oven temperature was programmed from 60 °C to 250 °C at 3 °C/min, with a final holding time of 10 min. Spectra were recorded in the electron impact mode (ionization energy, 70 eV) in a range of 15–550 amu at 2.9 scans/s. The identification of volatile compounds was achieved by comparing mass spectra with those of the data system library (NIST11, $p > 90\%$) and wherever possible by comparing retention times and mass spectra with those of commercially available standards. Moreover, a mixture of a continuous series of straight-chain hydrocarbons, C7–C30 (Alkane Standard Solution, Sigma Aldrich, Milan, Italy) was injected under the same conditions previously described to obtain the linear retention indices (RIs) (van Den Dool and Dec. Kratz 1963). The component relative percentages were calculated based on GC peak areas.

2.2 Antimicrobial Activity of Lavender Essential Oil

As target microorganisms, 6 strains belonging to the Culture Collection of the Laboratory of Predictive Microbiology

(University of Foggia, Italy) were used: *Staphylococcus aureus*, *Bacillus* spp., *Escherichia coli*, *Pseudomonas* spp., *Candida albicans*, and *Pichia membranifaciens*. All isolates were grown overnight in appropriate nutritive broths at their optimal temperatures before being used for antimicrobial activity tests. Inocula were prepared by diluting the exponentially growing cultures with physiological solution (0.9% NaCl) to obtain approximately 105 cfu/mL. To ensure a good degree of reproducibility in the inocula preparation, the cell counts were standardized through the direct plate count technique.

The LEO was dissolved in ethyl alcohol (95%) and then diluted with distilled water (50%, vol/vol) to enhance its water solubility. All stock solutions were freshly prepared before each use and sterilized by filtering through membranes (Minisart model 16534-K with 0.20-mm pore size; Sartorius, Goettingen, Germany). Finally, an aliquot of selected stock solutions was added to microbial suspensions to obtain LEO concentrations of 2, 4 and 8% (vol/vol) to assess the growth data on the selected microorganisms expressed as Inhibition Index (I.I.):

$$I.I. = \left[\frac{(A_c - A_s)}{A_c} \right] \times 100 \quad (1)$$

where A_c represents the absorbance of the SPC sample (without active solution but containing an appropriate amount of ethyl alcohol) and A_s is the absorbance of the samples + active compound (ACT). For the growth experiments, nutritive broths containing the active solution with an appropriate concentration of LEO were inoculated (1:10) with standardized cultures to yield one active test (ACT) for each microorganism under study. Evidence of microbial growth was acquired after 10 s of shaking by reading the absorbance changes at 420 nm with a UV-visible Beckman DU 600 spectrophotometer (Beckman Coulter, Inc., Fullerton, CA) at regular intervals. Inoculated media without LEO or ethyl alcohol were used as primary positive controls (PPC) to evaluate the microbial growth under optimal conditions. Inoculated media without active solution but containing an appropriate amount of ethyl alcohol (1%, vol/vol) served as secondary positive controls (SPC) to test for a possible antagonist or synergistic activity of ethanol during growth assays. Analyses were performed twice over two different batches.

For each studied microbial target, to quantify the anti-microbial effect of LEO, build the inhibitory profile and calculate NIC (Non-Inhibitory Concentration) and MIC (Minimum inhibitory Concentration), the approach suggested by Bevilacqua et al. 2012 was followed. The NIC is the maximum concentration of LEO that does not affect the microbial growth, whereas the MIC is the lowest concentration which

resulted in the maintenance or reduction of inoculum viability (Carson et al. 1995). Specifically, for each time of analysis and each LEO concentration, data were modelled as Growth Index (GI) which is a time-dependent and dimensional parameter ranging from 0 to 100%. A GI value of 0 indicates no cell growth during experiments; whereas a GI value of 100 indicates that there is no change in turbidity between AT and SPC. A GI value greater than 100 indicates that the active compound enhances microbial growth. To build an inhibitory profile, the obtained GI values were modelled as a function of the concentration of the antimicrobial compound through a modified negative Gompertz equation, following Bevilacqua et al. (2012) and Zwietering et al. (1990).

2.3 Plant Material and Experimental Setup

Two independent radish crop cycles were conducted in winter/early spring 2024: Cycle 1 from January–February; Cycle 2 from March–April. Both cycles followed the same experimental setup, substrate, and treatment protocol, differing only in environmental conditions due to seasonal variation. The average air temperatures were 17.2°C and 20.9°C during Cycle 1 and Cycle 2, respectively. In addition, the 4.0% LEO treatment was omitted in Cycle 2 because of the phytotoxic effects observed in Cycle 1. Radish seeds (Cv *saxa*, Bioseme®) were grown in an unheated glasshouse at the Experimental Farm of the University of Sassari in Ottava, Sassari, Sardinia, Italy (41°N, 8°E, 80 m a.s.l.). Radish plants were grown in pots (40×20×16 cm) containing 6 L of topsoil (TerComposti semine bio, Calvisano, Italy). 10 mL of Bayer Garden - Bayfolan® (10 mL/2L) were used as fertilizer before sowing. Twenty seeds per pot were initially planted and 5 plants per pots were maintained for the experiment. The biometric measurements were conducted once a week for 5 weeks.

2.4 Plant Treatments

A stock solution was prepared using Lavender essential oil (LEO), Polysorbate 80 Biorigin (15% of LEO used) and distilled water (Supplementary Material, Table [ESM2](#)). Polysorbate 80 is an emulsifier that enhances the dilution of the LEO in water. At the stage of 2 true leaves (stage 1.12 of the BBCH phenological scale (Meier 2001), plants were subjected to the following treatments:

- Control with water (H₂O).
- Control Polysorbate 80 (P80).
- Polysorbate 80 + Water + LEO (0.5%) (EO0.5).
- Polysorbate 80 + Water + LEO (1.0%) (EO1.0).
- Polysorbate 80 + Water + LEO (2.0%) (EO2.0).
- Polysorbate 80 + Water + LEO (4.0%) (EO4.0).

All treatments were applied using Gloria® Pro 5 Oil-proof version to micro-spray the test solution uniformly on the aerial part of the plant. Each treatment had 5 replicates of 5 plants each. The experiment was set up as a randomized block design and the greenhouse temperature was measured with a thermohygrometer (Mela KPC2-ME, Galtec, Germany).

2.5 Plant Biometric and Biomass Parameters

Plant growth and development were monitored weekly using the BBCH phenological scale. The following parameters were recorded: number of leaves (LN), leaf length in cm (LL), plant height in cm (PH), culm height in cm (CH), the collar diameter in mm (CD), and the root length in cm (RL). The leaf area in cm² (LA), including the total number of leaves per plant and the ratio of the leaf area over the number of leaves per plant (LA/LN in cm²) was measured using a planimeter (LI-3100c area meter, Li-Cor, Lincoln, NE, USA).

The following biomass parameters were measured: fresh and dry weight of the aerial part (APFW and APDW), radish fresh, dry weight and diameter (RadFW, RadDW and RD), root fresh and dry weight (RFW and RDW) and the leaf fresh weight (LFW) were evaluated. DW was measured after drying the plant samples for 72 h at 60 °C. Three plants per replicate were used for all above-described measurements. Dualex™ (FORCE-A, Orsay, France) was used at 1 week intervals to determine the relative chlorophyll content (CHL), flavonoid (FL) content and Nitrogen balance index (NBI). The relative CHL and FL content in leaves were estimated based on the CHL fluorescence excitation spectra (Ceric et al. 2005) on 5 fully expanded and healthy leaves of 3 plants per treatment.

2.5.1 Mineral Content

After nitric-perchloric digestion, K, Ca, Mg, Na, Mn, Zn and Cu were determined through atomic absorption spectrophotometry (AAS240 FS Varian, Australia) (ICP/MS) while Organic N was determined by Kjeldahl distillation after sample digestion with H₂SO₄.

2.6 Statistical Analysis

All results were subjected to normality test (Shapiro–Wilk test) before the statistical analysis. The statistical differences in NIC/MIC values were analysed with one-way ANOVA and Tukey's test ($p < 0.05$). Biometric, biomass parameters and mineral content were analysed with a two-way ANOVA (Cycle × Treatment) and LSD test ($p < 0.05$) to assess the statistical differences between Cycles and treatments using

the Minitab 17 Statistical Software 2010(State College, United States. Minitab, Inc.).

3 RESULTS

3.1 Chemical Composition of the Lavender Essential Oil

The GC-MS analysis of the LEO revealed the presence of 32 compounds listed in Table 1, accounting for 97.4% of the total composition. The main constituents were oxygenated monoterpenes including Linalool (36.81%) and its acetic ester (Linalyl acetate, 41.0%), in agreement with the qualitative composition observed on *Lavandula officinalis* in another Mediterranean region like Morocco, considering that variations in the EO composition could be due to genetic

diversities (Diass et al. 2023). Other monoterpenes found at lower concentrations were Limonene (2.34%), Camphor (1.90%), Endo-Borneol (1.71%), Eucalyptol (1.58%) and β -Mircene (1.49%).

Figure 1 shows the inhibition index (I.I.) measured for each microbial target after 48 h of contact time with LEO, which is the time necessary to reach the stationary phase for all tested microorganisms in optimal conditions. As expected, the inhibition increased following the increase of the LEO concentration, with some significant differences among strains. Particularly, the more sensible microorganism appeared *Staphylococcus aureus* which showed the highest growth inhibition (I.I. about 89%) when LEO was used at 8% (vol/vol). On the contrary, *Escherichia coli* was the more resistant strain: even when LEO was used at its maximum concentration, I.I. was only 15%. For the other species, the susceptibility to LEO inhibitory effect could be established in the following order: *Staphylococcus aureus* > *Pichia membranifaciens* > *Candida albicans* > *Bacillus* spp. > *Pseudomonas* spp. > *Escherichia coli*.

To quantify the potential biostatic or biocidal activity of LEO, growth kinetics and dose-response profiles were obtained and analysed. Therefore, Eq. 2 was fitted to the GI data obtained after 48 h versus tested LEO concentrations. The inhibition profiles are reported in Fig. 2. Results proved that the microbial susceptibility to LEO was non-linearly dose related. Each dose-response curve could be subdivided into three primary regions describing the microbial susceptibility to the compound. The first region lying below the NIC (Growth region) defined a range of LEO concentrations that did not significantly affect microbial growth. The non-linear dose-dependent increase of the antimicrobial activity was proved within an intermediate region bounded by NICs and MICs where the observed sigmoidal trend of the inhibitory profile allows to hypothesise a high-order kinetics for the microbial inhibition within this range. Measurable bacterial growth was not detectable within a third region of the inhibition profile above the MIC (No-growth region). In addition, the growth and no-growth regions were accurately individuated by determining both the NIC and MIC parameters, respectively (Table 2). Some differences in sensitivity to the tested oil were recovered among microbial targets; in general, all microorganisms showed NIC levels of about 40 mg/mL, except *St. aureus* and *E. coli*, which were characterised by the greatest sensitivity (lowest NIC value, about 20 mg/mL) and the greatest resistance (highest NIC value, about 80 mg/mL) against LEO, respectively. The possibility of completely inhibiting microbial growth is related to the use of LEO at the MIC level at least: the MIC values were not statistically different between microorganisms and were around 150–160 mg mL⁻¹.

Table 1 *Lavandula angustifolia* essential oil (LEO) composition

Peak No.	Compound	R.T.	RI _{Lit} ¹	RI _{Exp} ²	Area (%)
1	α -Pinene	12.276	917	915	0.22
2	Camphene	12.933	933	931	0.14
3	β -Pinene	14.202	964	963	0.34
4	3-Octanone	14.545	985	983	0.52
5	β -Myrcene	14.741	992	989	1.49
6	o-Cymene	16.375	1021	1019	0.63
7	Limonene	16.582	1035	1031	2.34
8	Eucalyptol	16.718	1046	1045	1.58
9	trans- β -Ocimene	16.923	1054	1051	0.35
10	cis- β -Ocimene	17.425	1038	1036	0.64
11	Linalool oxide II	18.656	1072	1071	0.58
12	Linalool	20.127	1099	1097	36.81
13	1-Octen-3-ol, acetate	20.430	1112	1111	0.10
14	Plinol C	21.124	1114	1121	0.23
15	Camphor	22.097	1144	1141	1.9
16	Terpinen-1-ol	21.533	1172	1169	0.10
17	endo-Borneol	23.073	1160	1158	1.71
18	Terpinen-4-ol	23.574	1177	1175	0.51
19	α -Terpineol	24.180	1182	1185	1.46
20	Geraniol	25.830	1240	1231	0.13
21	Linalyl acetate	27.205	1247	1251	41.011
22	Geranial	27.686	1268	1274	0.10
23	Bornyl acetate	28.432	1287	1285	0.56
24	Lavandulyl acetate	28.512	1292	1291	0.52
25	Neryl acetate	31.636	1361	1365	0.63
26	α -Copaene	32.293	1372	1376	0.10
27	Geranyl acetate	32.436	1381	1384	1.11
28	Caryophyllene	34.12	1414	1411	0.31
29	Germacrene D	37.787	1575	1571	0.10
30	Caryophyllene oxide	40.500	1583	1581	0.98
31	Humulene-1,2-epoxide	41.434	1602	1606	0.10
32	(+)-alfa-Bisabolol	43.956	1685	1682	0.10

¹RI_{Lit} = Linear retention index from literature (van Den Dool and Kratz 1963); ²RI_{Exp} = Determined linear retention index against mixture of n-alkanes (C7-C30) on HP-5MS column

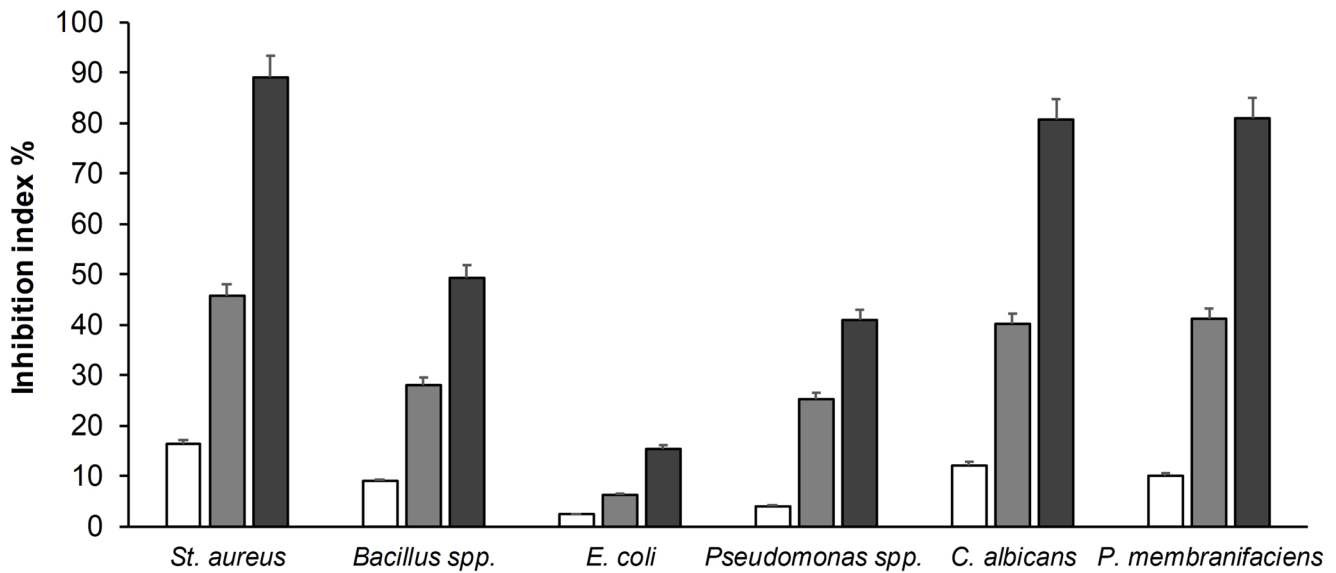


Fig. 1 *Lavandula angustifolia* essential oil Inhibition index (I.I.) and related standard deviation observed at 2% (white bars), 4% (grey bars) and 8% (black bars) concentration against *St. aureus*, *Bacillus spp.*, *E.*

coli, *Pseudomonas spp.*, *C. albicans* and *P. membranifaciens* after 48 h in nutritive broths

3.2 Radish Growth and Development

The average greenhouse temperature was 17.2 °C and 20.9 °C in the first (January–February) and the second (March–April) Cycle, respectively. The radish growth varied significantly as a result of specific concentrations of LEO. Significant data for biometric, biomass and pigments parameters for both cycles were reported in Supplementary Material, Table ESM3. After Cycle 1, the toxicity level of LEO for radish was found at 4.0%, with several stress symptoms in most of the sample plants 30 min after its spray, including necrotic lesions and leaf rolling in the aerial parts that caused a significant reduction of plant growth and development (Supplementary Material, Fig. ESM1). Accordingly, the 4.0% concentration was not repeated in Cycle 2.

In Cycle 1, the Leaf number (LN), plant height (PH), leaf length (LL) and average leaf area per leaf (LA/LN) were the biometric parameters affected by the LEO treatments (Table 3). For all these biometric characters, the EO4.0 treatment induced visibly phytotoxic effects, with a significant reduction of plant growth and development. Conversely, LEO concentrations between 0.5% and 2.0% produced small, but consistent increases in these parameters compared to the controls, suggesting a mild biostimulant effect limited to this concentration range. LN ranged from 5.56 (EO4.0) to 7.00 (EO1.0). PH revealed the highest value in P80 control and EO1.0, (15.73 cm and 15.40 cm respectively), whereas the shortest plant was recorded under EO4.0 (13.18 cm). LL and LA/LN revealed similar trends: in both cases, the highest value was under EO2.0 with 13.80 cm and

38.51 cm² for LL and LA/LN respectively. In addition, the lowest values were found under EO4.0 (10.92 cm and 25.54 cm² for LL and LA/LN respectively). Finally, CD ranged from a minimum value of 6.00 mm (EO4.0) to a maximum value of 8.03 mm in the H₂O control. These two treatments were the only ones statistically different in terms of CD. Besides the biometric parameters, also the fresh biomass was analyzed on the aerial part, leaves, radish and roots (APFW, LFW, RadFW, RFW, respectively) (Fig. 3). Except for RadFW, where statistical differences between treatments were minimal, all the other fresh biomass parameters were significantly affected by the treatments during Cycle 1.

As observed for the the biometric parameters, the EO4.0 treatment showed the lowest values of APFW, LFW and RFW. A similar biomass reduction on EO4.0 was observed on the dry weight (APDW), whereas the differences in the dry weight of the roots (RDW) and radish (RadDW) were not significant both between treatments and cycles (Supplementary Material, Table ESM4). The APFW from EO0.5 to EO2.0 treatments was statistically similar, with the highest value observed under EO2.0 (13.44 g), which resulted 25% higher than the control in H₂O. LFW was highest under EO2.0 and P80 (10.46 and 9.84 g, respectively). Finally, RFW under EO0.5 was 0.49 g, close to that observed at EO1.0 and EO2.0 treatment.

Similarly to Cycle 1, in Cycle 2 PH, LL, LA/LN were significantly affected by the treatments (Table 3). Indeed, the radish diameter (RD) increased with the LEO concentrations, up to 31.42 mm in EO2.0, even if it was not significant. PH ranged from the minimum of 11.98 cm

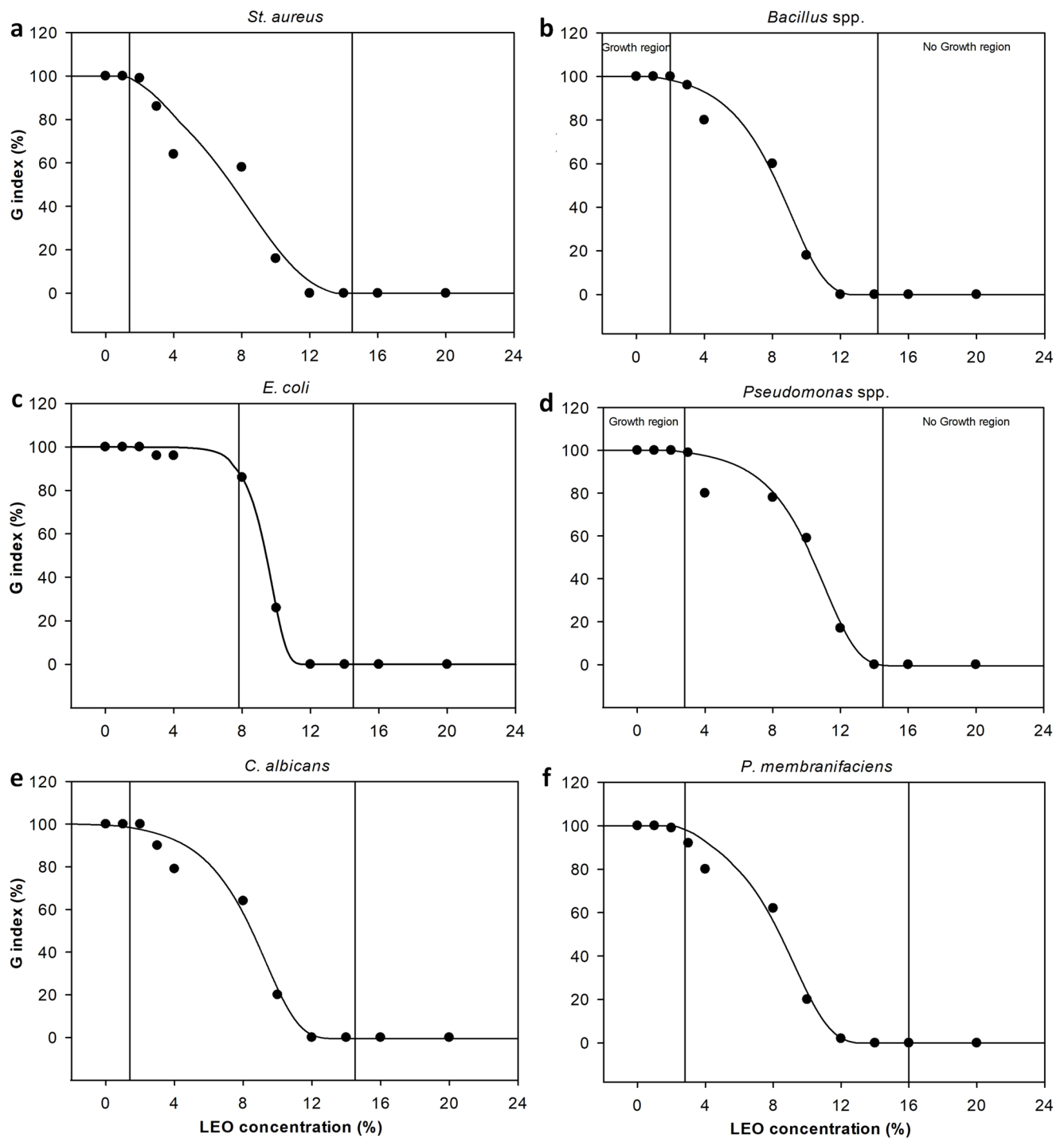


Fig. 2 Dose-response profiles after 48 h exposure to *Lavandula angustifolia* essential oil (LEO) expressed as Growth Index (G. Index) on *St. aureus* (a), *Bacillus* spp. (b), *E. coli* (c), *Pseudomonas* spp. (d), *C.*

albicans (e) and *P. membranifaciens* (f). The first and the second black vertical line of each graph represents the Not-Inhibitory Concentration (NIC) and the Minimal Inhibitory Concentration (MIC), respectively

(P80) to the maximum of 14.60 cm (EO1.0), revealing significant differences between these two treatments. Comparable results were observed on LL, LA/LN, and RD, where the maximum values were recorded under EO2.0 (13.44 cm, 44.04 cm², and 31.42 mm for LL, LA/LN and

RD, respectively. In addition, for LL the minimum value was found under control conditions (H₂O and P80), which significantly differentiated to EO1.0 and EO2.0 treatments. For LA/LN, in the presence of EO1.0 and EO2.0, plants showed a significant increase in average leaf area compared

Table 2 NIC (Not-Inhibitory Concentration) and MIC (Minimal inhibitory Concentration) values of *Lavandula angustifolia* essential oil (LEO). Data is presented as mean $\pm$ standard deviation. Different letters in the columns indicate significant differences (Tukey test, $p < 0.05$)

Microorganisms	NIC (mg mL ⁻¹)	MIC (mg mL ⁻¹)
<i>Staphylococcus aureus</i>	19.6 $\pm$ 2.90 ^a	163.5 $\pm$ 7.90 ^a
<i>Bacillus</i> spp.	36.8 $\pm$ 10.4 ^b	155.1 $\pm$ 10.4 ^a
<i>Escherichia coli</i>	77.0 $\pm$ 10.2 ^c	147.6 $\pm$ 10.2 ^a
<i>Pseudomonas</i> spp.	34.5 $\pm$ 9.20 ^b	155.7 $\pm$ 9.20 ^a
<i>Candida albicans</i>	34.0 $\pm$ 12.0 ^b	157.6 $\pm$ 12.0 ^a
<i>Pichia membranifaciens</i>	29.7 $\pm$ 8.20 ^b	154.3 $\pm$ 8.20 ^a

to the other treatments. Finally, the RD treated with LEO levels statistically improved in all treatments compared to controls (H₂O and P80).

In terms of fresh biomass, APFW, LFW, and RadFW showed significant differences based on the treatment, which generally increased with the LEO. A similar trend can be observed for APFW and LFW: in both cases EO2.0 induced the best plant response with the highest APFW and LFW (14.24 g and 11.21 g respectively), similar to the EO1.0 treatment. The RadFW, showed the highest value on the EO2.0 treatment (17.72 g). However, no significant differences were found with all the other treatments except for P80 which showed the lowest value (7.29 g).

3.3 Leaf Pigment Estimation and Mineral Content

The Chlorophyll (Chl), Flavonoid (Flav), Anthocyanins (Anth) and Nitrogen balance index (NBI) were measured using Dualex. These leaf fluorescence indexes showed significant differences on both cycles, except the Anth of Cycle 2 (Supplementary Material, Table ESM3). Table 4

reports the results of both Cycles. Significant differences among all fluorescence indexes were found: the Chl pigment showed the minimum value under EO4.0 (21.4 $\mu\text{g cm}^{-2}$) while the highest was recorded under EO1.0 (26.9 $\mu\text{g cm}^{-2}$). Comparable results were observed between all LEO treatments and controls. In Cycle 2, the overall Chl was significantly higher (24.2 $\mu\text{g cm}^{-2}$) under EO2.0 compared to the other treatments at lower LEO concentration (21.5 $\mu\text{g cm}^{-2}$). Slight or no differences were observed on Anth and Flav between treatments and cycles, whereas NBI was significantly reduced only at EO4.0 concentration on both cycles.

The average concentration of both macro and micronutrients was higher in Cycle 2 (an exception was N, which remained average concentrations around 3.0%) (Table 5). After Cycle 1 the concentrations of P were the highest in the EO0.5 treatment (5853 mg kg⁻¹), whereas K, Na, Ca and Mg did not show significant differences compared to controls in H₂O and P80, with the lowest concentrations in EO2.0 for K, Ca and Mg (53185, 2700 and 1100 mg kg⁻¹, respectively). As for the other micronutrients, Cu was highest in EO1.0, Zn was not significantly affected by the LEO and Mn resulted the highest in the H₂O control (16.53 mg kg⁻¹). After Cycle 2, the highest level of macro and micronutrients was observed in EO2.0, except on K, which was similar to or lower than the controls in H₂O and P80 (highest on H₂O with 77716 mg kg⁻¹). The average concentration of minerals observed in both cycles was always higher than the standard chemical composition of radish (Valori alimenti 2024), except for N (same concentration of 3.0%). Overall, pigment and nutrient responses indicated a mild biostimulant effect. The slight increase in Chl at EO1.0–2.0 and minor variations in P and Cu suggest limited physiological stimulation rather than a strong biostimulant action.

Table 3 Biometric parameters monitored in cycle 1 and 2. Leaf number (LN), plant height (PH), leaf length (LL), leaf area per number of leaf (LA/LN), radish diameter (Rad D), root length (RL), culm height (CH) and collar diameter (CD) are reported. Each cycle has been analysed separately. Plants were treated with *Lavandula angustifolia* essential oil (LEO) at 4 levels of essential oil (EO) (from 0.5 to 4.0%) in cycle 1 and 3 levels in cycle 2. H₂O and P80 were added as controls with water and polysorbate 80, respectively. Different letters show significant differences (LSD test, $p < 0.05$) for post hoc comparisons for each cycle

Cycle	Treatment	LN	PH (cm)	LL (cm)	LA/LN (cm ²)	RD (mm)	RL (cm)	CulmH (cm)	CD (mm)
Cycle 1	H ₂ O	5.88 $\pm$ 0.83ab	13.74 $\pm$ 0.91ab	11.49 $\pm$ 0.88bc	36.43 $\pm$ 12.10ab	31.09 $\pm$ 5.50	10.03 $\pm$ 1.58	1.54 $\pm$ 0.07	8.03 $\pm$ 0.89
	P80	6.38 $\pm$ 0.92ab	15.73 $\pm$ 1.87a	12.93 $\pm$ 2.03ab	36.25 $\pm$ 9.11ab	27.10 $\pm$ 6.60	9.70 $\pm$ 1.59	1.21 $\pm$ 0.04	6.69 $\pm$ 1.65
	EO0.5	6.17 $\pm$ 0.41ab	14.27 $\pm$ 1.57ab	12.17 $\pm$ 0.80abc	33.31 $\pm$ 3.68ab	25.75 $\pm$ 3.31	10.23 $\pm$ 0.89	1.43 $\pm$ 0.09	6.82 $\pm$ 1.40
	EO1.0	7.00 $\pm$ 0.82a	15.40 $\pm$ 1.10a	13.32 $\pm$ 1.19a	36.15 $\pm$ 7.13ab	25.53 $\pm$ 5.07	10.10 $\pm$ 0.84	2.11 $\pm$ 0.02	7.50 $\pm$ 1.16
	EO2.0	6.00 $\pm$ 0.93ab	14.81 $\pm$ 1.41ab	13.80 $\pm$ 0.53a	38.51 $\pm$ 10.12a	29.25 $\pm$ 4.35	10.50 $\pm$ 0.99	1.76 $\pm$ 0.01	6.78 $\pm$ 1.56
	EO4.0	5.56 $\pm$ 0.73b	13.18 $\pm$ 0.98b	10.92 $\pm$ 0.77c	25.54 $\pm$ 5.06b	30.13 $\pm$ 2.20	9.80 $\pm$ 1.68	1.18 $\pm$ 0.01	6.00 $\pm$ 1.15
Cycle 2	H ₂ O	7.20 $\pm$ 0.63	12.56 $\pm$ 1.32bc	11.11 $\pm$ 1.06c	34.50 $\pm$ 3.34b	26.53 $\pm$ 9.62ab	9.31 $\pm$ 3.63	1.35 $\pm$ 0.44	7.36 $\pm$ 0.74
	P80	6.75 $\pm$ 0.46	11.98 $\pm$ 0.90c	11.00 $\pm$ 1.12c	33.45 $\pm$ 1.75b	19.66 $\pm$ 10.30b	8.99 $\pm$ 0.69	2.33 $\pm$ 0.41	6.03 $\pm$ 0.79
	EO0.5	6.45 $\pm$ 0.82	12.51 $\pm$ 0.49bc	11.39 $\pm$ 0.55bc	36.55 $\pm$ 3.76b	29.84 $\pm$ 5.09a	9.51 $\pm$ 1.41	1.05 $\pm$ 0.32	6.35 $\pm$ 1.72
	EO1.0	7.14 $\pm$ 0.90	14.60 $\pm$ 0.58a	13.44 $\pm$ 0.86a	44.11 $\pm$ 3.06a	30.67 $\pm$ 2.44a	9.10 $\pm$ 0.83	1.43 $\pm$ 0.53	7.49 $\pm$ 1.15
	EO2.0	6.82 $\pm$ 0.98	13.27 $\pm$ 0.61b	12.29 $\pm$ 0.92ab	41.37 $\pm$ 1.56a	31.42 $\pm$ 3.47a	8.95 $\pm$ 0.99	1.19 $\pm$ 0.45	6.74 $\pm$ 1.13

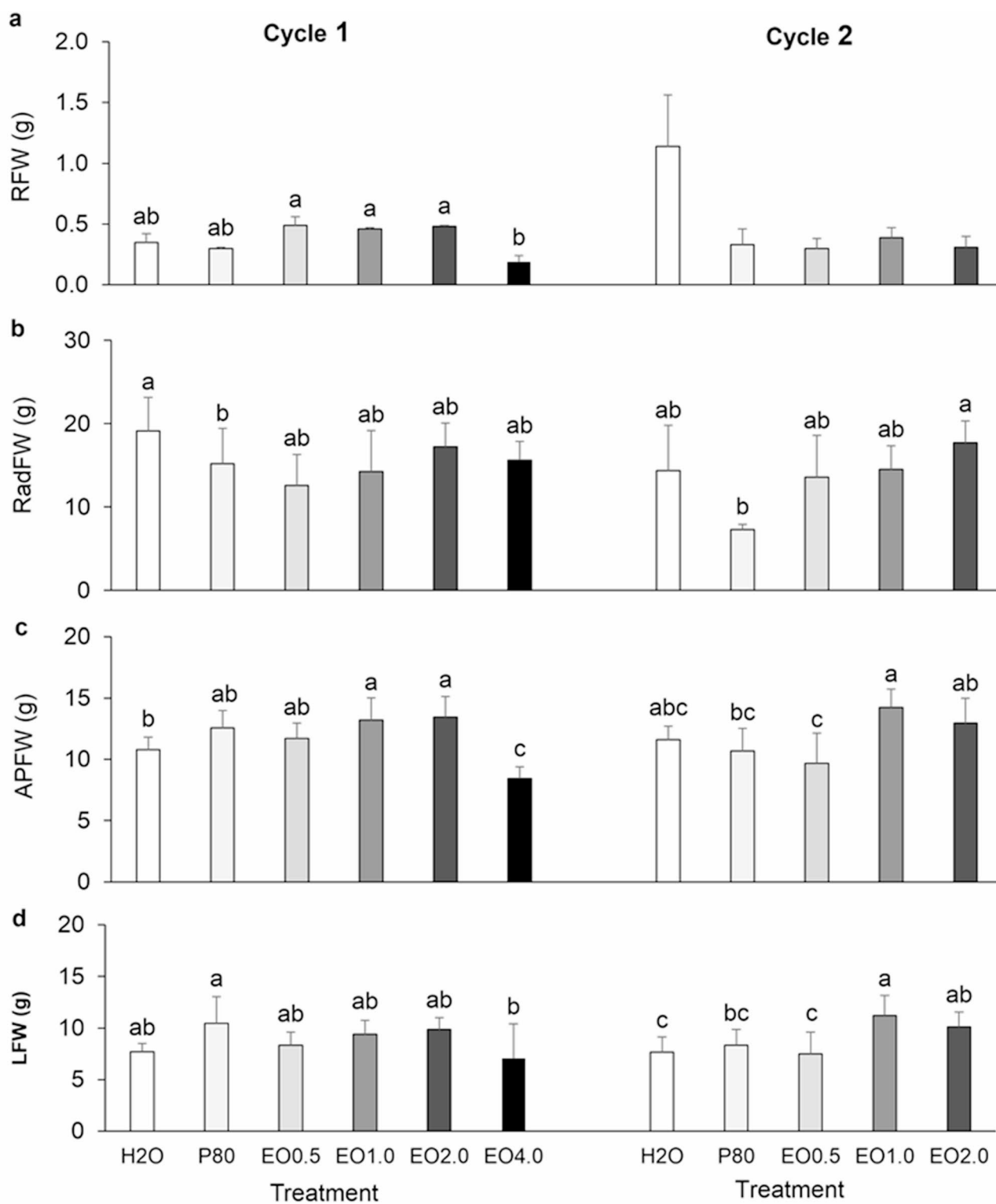


Fig. 3 Fresh weight of the root (RFW) (**A**), radish (RadFW) (**B**), aerial part (APFW) (**C**) and leaves (LFW) of the plants (**D**) treated with *Lavandula angustifolia* essential oil (LEO). Each Cycle has been analysed separately. Plants were treated with 4 levels of essential oil (EO)

(from 0.5 to 4.0%) in Cycle 1 and 3 levels in Cycle 2. H₂O and P80 were added as controls with water and polysorbate 80, respectively. Different letters show significant differences (LSD test, $p < 0.05$)

Table 4 Fluorescence indexes of radish leaves treated with *Lavandula angustifolia* essential oil (LEO). The average value and the standard deviation of dual indexes are reported: chlorophyll content (Chl), total flavonols (Flav), total anthocyanins (Anth), nitrogen balance index (NBI). Each cycle has been analysed separately. Plants were treated with 4 levels of essential oil (EO) (from 0.5 to 4.0%) in cycle 1 and 3 levels in cycle 2. H₂O and P80 were added as controls with water and polysorbate 80, respectively. Different letters show significant differences (LSD test, $p < 0.05$)

Cycle	Treatment	Chl	Flav	Anth	NBI
Cycle1	H ₂ O	24.4 ± 1.3ab	0.25 ± 0.02ab	0.73 ± 0.02	139.3 ± 3.9ab
	P80	25.4 ± 0.3ab	0.27 ± 0.03ab	0.72 ± 0.06	128.9 ± 2.5ab
	EO0.5	23.9 ± 0.2b	0.24 ± 0.04ab	0.73 ± 0.01	132.6 ± 9.4ab
	EO1.0	26.9 ± 0.8a	0.22 ± 0.01b	0.72 ± 0.01	156.2 ± 15.5a
	EO2.0	24.5 ± 1.9ab	0.22 ± 0.02b	0.73 ± 0.02	102.1 ± 22.9bc
	EO4.0	23.8 ± 1.4b	0.29 ± 0.01a	0.73 ± 0.02	90.3 ± 11.5c
Cycle2	H ₂ O	22.4 ± 2.0ab	0.27 ± 0.06	0.72 ± 0.04	104.3 ± 78.2
	P80	22.4 ± 1.5ab	0.27 ± 0.03	0.71 ± 0.02	148.6 ± 77.1
	EO0.5	21.4 ± 1.6b	0.27 ± 0.09	0.69 ± 0.11	154.2 ± 37.0
	EO1.0	21.5 ± 1.6b	0.26 ± 0.04	0.71 ± 0.01	154.7 ± 48.9
	EO2.0	24.2 ± 1.5a	0.28 ± 0.04	0.69 ± 0.02	101.5 ± 26.3

4 Discussion

Research studies have been conducted on the antimicrobial properties of LEO. These studies have been done *in vitro*. However, it is challenging to draw definitive conclusions, due to high variability of its chemical composition. EO in fact can deeply vary based on plant variety, growing season, and geographical origin (Fokou et al. 2020). The antimicrobial efficacy of lavender essential oil (LEO) can be primarily attributed to its high linalool content (approximately > 37%) of the oil's composition. Linalool has been consistently reported as the principal active component underlying the antimicrobial and antifungal properties of LEO (Aelenei et al. 2019; Parasuraman et al. 2022; Shen et al. 2022; Shin et al. 2014). El-Said et al. (2021) reported that the essential oil hydrodistilled from the flowering aerial parts of *Lavandula pubescens* Decne exhibited notable inhibitory activity against a range of Gram-positive and Gram-negative bacteria. In particular, significant sensitivity was observed in *Acinetobacter baumannii*, *Salmonella typhimurium*, *Shigella sonnei*, *Enterococcus faecalis*, and *Staphylococcus epidermidis*. These results support the hypothesis that linalool plays a key role in the broad-spectrum antimicrobial activity of LEO and highlight its potential as a natural alternative to conventional antimicrobial agents.

Staphylococcus aureus (Gram-positive) and *Escherichia coli* (Gram-negative) exhibited the highest sensitivity (NIC value of around 20 mg/mL) and resistance (NIC value of around 80 mg/mL), respectively, to LEO. These results align with those of Adaszyńska-Skwirzyńska and Dzięcioł (2017), who reported that Gram-positive bacteria were most susceptible to EOs derived from lavender flowers. *Pseudomonas spp.* exhibited about 40% inhibited growth when LEO was used at 8.0%; however, the same oil concentration was highly effective against *C. albicans*, with over 80% growth inhibition.

Caprari et al. (2021) reported that essential oils extracted from dried and fresh flowers of *L. angustifolia* grown in central Italy significantly inhibited *Bacillus subtilis* and *Escherichia coli* growth, showing a bactericidal effect on *E. coli* at higher concentrations of oil from fresh flowers. In contrast, our results identify *E. coli* the most resistant bacteria. Hossain et al. (2017) demonstrated the antimicrobial activity of *L. angustifolia* essential oil against 38 pathogenic bacterial strains. Our results demonstrated the effectiveness of LEO against all tested bacteria, with the exception of *Pseudomonas aeruginosa*. In contrast, significant antimicrobial activity of LEO from Turkey was observed against *Ps. aeruginosa* (Turgut et al. 2017). Finally, strong antimicrobial activity was also noted against *Candida albicans*, *St. aureus*, and *Aspergillus brasiliensis*. The above considerations confirmed the importance of the EO phytochemical composition in its antimicrobial effectiveness. Overall, the observed variability in antimicrobial activity may be attributed to differences in bacterial strains tested, plant species, geographic origin, plant parts used for extraction, phenological stage, and cultivation practices. These factors can significantly influence the volatile composition of essential oils, emphasizing the necessity of standardization before their use as biostimulant agents or food additives.

The application of biostimulants on crop species affects plant metabolism and eventually can improve edible quality (Colla et al. 2015). In our study, LEO's chemical composition highlighted that monoterpenes are the primary components (Table 1), suggesting its potential activity as elicitor of plant growth. Indeed, these compounds are produced by plants as allelopathic substances capable of affecting the growth and development of nearby or competing species in the plant community (Singh et al. 2002). The biostimulant effects of LEO on radish have been assessed with biometric, biomass and physiological parameters, showing significant effects between the two Cycles on all biomass parameters,

Table 5 Mineral content of radish tubers treated with *Lavandula angustifolia* essential oil (LEO). Plants were treated with 4 levels of essential oil (EO) (from 0.5 to 4.0%) in cycle 1 and 3 levels in cycle 2 (from 0.5 to 2.0%). H₂O and P80 were added as controls with water and polysorbate 80, respectively. The average value and the standard deviation are reported. Each cycle has been analysed separately. Different letters show significant differences (LSD test, $p < 0.05$)

Cycle	Treatment	Macroelements			Microelements					
		N	P	K	Na	Ca	Mg	Mn	Cu	Zn
Cycle 1	H ₂ O	3.20±0.16ab	5164±195 cd	64,075±4015b	2048±158c	4450±866a	1300±80c	16.53±0.23a	2.58±0.06c	41.51±2.23a
	P80	3.30±0.20a	5051±268d	66,513±3007b	2558±9a	4306±57a	1659±56b	9.92±0.74d	2.12±0.13d	39.43±2.58b
	EO0.5	3.00±0.21bc	5853±247a	68,167±1452ab	2435±33a	4544±112a	1879±25a	15.09±1.14b	2.77±0.26b	38.49±0.60b
	EO1.0	3.05±0.20bc	5603±100b	71,503±8713ab	2231±160b	4704±486a	1914±248a	12.87±0.34c	3.98±0.11a	43.17±1.11a
	EO2.0	2.95±0.21c	5356±218c	53,185±1667c	2551±198a	2700±412b	1100±190d	12.57±0.82c	2.13±0.07d	38.41±0.95b
	EO4.0	3.05±0.15bc	5139±333 cd	71,547±713ab	2180±162c	3928±204a	1703±42b	11.47±0.20 cd	2.70±0.37b	39.85±4.46b
Cycle 2	H ₂ O	2.85±0.16 cd	5366±307c	77,716±4089a	3528±300b	3984±312c	1523±116d	21.17±0.13a	3.94±0.15e	38.29±1.84d
	P80	3.10±0.21b	6098±190a	75,001±1272b	3543±133b	4361±93b	1815±36b	14.38±0.00b	2.76±0.24c	44.13±2.47b
	EO0.5	2.60±0.21d	6084±185a	61,395±2809c	3703±167b	4232±103b	1845±57b	14.54±1.14b	4.32±0.16d	37.80±1.41d
	EO1.0	2.70±0.21 cd	5731±269b	60,712±1746c	2573±112c	4000±209c	1667±104c	21.33±0.07c	3.84±0.16a	40.08±1.02 cd
	EO2.0	3.35±0.16a	6195±296a	73,743±1752b	4015±167a	4770±234a	2196±31a	25.83±0.06a	4.15±0.16b	45.96±1.61a

due to the different microclimate conditions (Fig. 3). Overall, most radish biometric parameters showed higher values during Cycle (1) Both yield and roots and aerial part fresh weight resulted greater than those observed in Cycle (2) However, only slight or non-significant differences were detected among treatments ranging from 0.5% to 2.0%, suggesting a weak or negligible biostimulant effect of LEO at the tested concentrations. Plant height and leaf biometric parameters (leaf area and plant fresh weight) increased at EO1.0 treatment in both cycles, although differences were observed between them. These variations were primarily attributed to temperature, as Cycle 1 was conducted at a lower average temperature (17.2 °C) compared to Cycle 2, which was 3.7 °C higher (20.9 °C). Radish is considered a cold season crop, even under greenhouse conditions, with an optimal temperature range between 10 and 15.5 °C for growth and product quality (Manzoor et al. 2021). The higher average temperature recorded in Cycle 2 may have induced mild heat stress, as indicated by the slightly reduced biometric and biomass values. These suboptimal conditions highlighted the influence of the essential oil, suggesting that LEO activity in radish may be more effective under specific environmental conditions that enhance its biostimulant potential. Finally, no statistical differences were detected on the biometric and biomass parameters till the LEO concentration of 2.0%. Most of the biometric parameters increased with the LEO concentration, reaching the maximum at EO1.0 or EO2.0, followed by a decrease at higher LEO concentrations (4.0%), although this observation was not statistically significant. These slight, but consistent increases at low concentrations suggest that LEO may act as a weak biostimulant within this range, with limited biological relevance rather than a strong stimulatory effect. Nonetheless, we should consider the possibility that LEO could elicit physiological alterations, analogues to those induced by plant hormones. These hormonal adjustment may potentially govern or augment vegetative development, ultimately achieving a maximal concentration. After this plant status the efficacy of the EO biostimulant is reduced or becomes deleterious to the crop. Indeed, at high EO concentration (EO4.0), the phytotoxic effects replaced the role of stress elicitor, with a considerable decrease of both plant and root biomass. The EO1.0 is probably the best concentration for radish to increase most of its biometric, biomass and pigment content. Souri and Bakhtiarizade (2019) reported an increase of root and shoot fresh weight of tomato seedling treated with rosemary EO (foliar or soil application). Our results are in partial agreement with this study; in fact, in Cycle 2 a higher but not significant plant and leaf fresh biomass was observed at EO1.0, except for root fresh weight, which reached the highest value at EO2.0. The application of LEO seemed to have a weakly biostimulant effect partly

comparable to the effects observed with the use of other organic compounds, i.e. humic acid, salicylic acid and vitamins (Souri and Römheld 2009; Marschner 2011; Denre et al. 2014; Rose et al. 2014). However, the overall biostimulant response observed in radish was mild, suggesting that an improved effect might require multiple applications, a longer exposure period, or a combination with other known biostimulant compounds. Most of the organic compounds, including water-soluble lignin extract (Savy et al. 2015) from several plant species are able to improve plant growth, nutrient uptake efficiency in different plant species (Russo and Berlyn 1991, 1992). The experimental trials ascertained the phytotoxic level of LEO at a concentration of 4.0%, which reduced the radish yield and the fresh biomass of both roots and aerial part of the plants, as well as a reduction of plant growth and leaf length. Although this concentration proved unsuitable for biostimulation, the consistent phytotoxicity observed highlights its herbicidal potential, warranting a follow-up study to assess efficacy in organic weed management. This concentration had a limited or no inhibition effect on the bacteria evaluated in this study, since a significant inhibition index higher than 80% was observed only from a concentration higher than 8.0%, whereas *Escherichia coli* required considerably higher concentrations (around 15%). As a consequence, the LEO concentrations tolerable for the horticultural crop (up to 2.0%) could not be effective as an antimicrobial treatment in the field. On the other hand, the phytotoxicity of the 4.0% concentration is promising to develop LEO-based organic herbicides as a sustainable alternative to synthetic products. The negative effects of EO4.0 on radish leaves could be associated to Camphor, Linalool and Eucalyptol compounds, have already been demonstrated to exhibit a phytotoxic activity on weeds (Ibáñez and Blázquez 2019). Therefore, the EOs and the related water extracts are currently under investigation as innovative weed control products able to play an important role in reducing the risks for the environment related to synthetic herbicides and the consequent potential development of herbicide-resistant species (Elghobashy et al. 2024; Verdeguer et al. 2020). Further trials should be conducted to determine the phytotoxic concentration and herbicidal efficacy of LEO on open-field crops, since the EOs are subjected to photodegradation, altering their toxicity pattern and suitability as antimicrobial compounds (Maria Beltrame et al. 2013).

Besides the consistent differences between the two Cycles, the concentrations of 2.0% or lower generally determined no particular and noticeable effects on either the leaf pigments (Table 4) and the macro and micronutrients on the radish tubers (Table 5), with negligible effects on the crop physiology and the nutritional mineral value of the tubers. The average mineral content considerably higher during the

second cycle (especially on Na and Ca) was attributable to the higher dry matter of radish (Supplementary Material, Table SM4) due to the higher temperature in summer and the consequent increase of mineral concentration on the tubers. The mild or negligible effects observed on plant biomass, biometric, leaf pigments and minerals between the treatments acceptable to the crop (LEO from 0.5 to 2.0%) were possibly due to the insufficient concentration or number of treatments. Multiple treatments administered from the early phenological stages could increase the antimicrobial activity at these concentrations and improve the LEO efficacy. Nevertheless, the present study was limited to a single foliar spray at one phenological stage under non-stress conditions, which should be addressed in future research. These considerations deserve further trials aimed at assessing the effects with multiple administrations, the causes of the phytotoxic effects and the potential application of LEO in sustainable and organic phytopathogen control, including tests for the decay time on the field and the absorption rate by the leaves.

5 Conclusions

The essential oils (EOs) are considered a promising alternative to conventional antimicrobial products in both integrated and organic agriculture. In this study, one foliar application of lavandula essential oil (LEO) with a concentration up to 4.0% revealed mild positive effects on the biometric, biomass and leaf pigments of radish, also probably influenced by the environmental conditions of the two Cycles. The main constituents were the oxygenated monoterpenes linalool and linalin acetate, which showed an effective antimicrobial and phytotoxic activity at concentrations equal or higher than 8.0%. According to this, further investigations should be conducted to explore the biostimulant effect of LEO and the antimicrobial properties as biopesticide with periodic administrations during the crop cycle. In addition, considering the fragmented data available on the potential physiological mechanisms biostimulant and allelopathic LEO activity, a deep investigation of the signal molecules involved in plant growth and development under LEO treatment would be desirable. In perspective, the efficacy of LEO as a bioactive compound against fungal and viral phytopathogens should be studied at concentrations tolerable to the crops (around or lower than 4.0%) and with multiple treatments per cycle, also taking into account its eco-safety to non-target organisms of the agroecosystems.

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Data Availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Ethical Approval Not applicable.

Consent To Participate Not applicable.

Consent To Publish Not applicable.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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