



## Research article

Impact of composts from decentralized composting models on *R. officinalis* physiology and nutrient contents under abiotic stress

C. Álvarez-Alonso <sup>a</sup> , I. Nogues <sup>b,\*</sup> , E. Pallozzi <sup>b,c</sup> , W. Stefanoni <sup>b</sup> , F. Pietrini <sup>b,c</sup> ,  
L. Sosa <sup>d</sup> , N. Manrique-Cordoba <sup>a</sup> , M.D. Perez-Murcia <sup>a</sup> , R. Moral <sup>a</sup> , M.A. Bustamante <sup>a</sup> 

<sup>a</sup> CIAGRO, Universidad Miguel Hernández, EPS-Orihuela, Ctra. Beniel, Km 3.2, Orihuela, 03312, Alicante, Italy

<sup>b</sup> Research Institute of Terrestrial Ecosystems, National Research Council, Via Salaria Km 29,300, 00015, Monterotondo, Italy

<sup>c</sup> NBFC, National Biodiversity Future Center, 90133, Palermo, Italy

<sup>d</sup> Department of Ecological and Biological Sciences, University of Tuscia, Largo Dell'Università, 01100, Viterbo, Italy

## ARTICLE INFO

## Keywords:

Drought

Salinity

Organic amendments

Monoterpenes

Photosynthesis

Reflectance

## ABSTRACT

The loss of organic matter in soils, in conjunction with water scarcity and salinization constitutes a grave problem in the Mediterranean region. The utilization of composts derived from novel decentralized models, such as agrocomposting, community composting and decentralized urban composting, is hypothesized as an effective strategy with the potential to enhance the physical, chemical and biological characteristics of the soil. The application of compost has been demonstrated to enhance the resilience of plants to abiotic stresses, including drought and salinity. In this context, eight decentralized model composts were employed as organic amendments in a degraded soil to assess whether they could mitigate the stress experienced by the Mediterranean shrub *R. officinalis* under conditions of drought or salinity for one month. Therefore, measurements of gas exchange, emission of volatile organic compounds and reflectance during stress were performed in order to determine the degree of adaptation of the plants. Composts from community composting were found to be more effective in alleviating the effects of abiotic stress, while the ineffectiveness of composts from decentralized urban composting depended on their characteristics (e.g. humic substances and electrical conductivity). An initial increase in monoterpene emission rates was observed, which decreased at the end of the experimental time in a positive correlation with leaf RWC. Stress also led to a reduction in photosynthesis (A) and stomatal conductance (gs). Reflectance was more affected under drought conditions and by the application of compost with a high electrical conductivity, which likely hindered chlorophyll synthesis. Thus, the present results have enabled the selection of appropriate composts for utilization in agriculture under stress conditions considering plant biomass values and compost characteristics (EC, humic substances content, and the K/Na ratio).

## 1. Introduction

The degradation of soil quality, primarily driven by the loss of organic matter and biodiversity, has been recognized as a critical environmental concern (Caon and Vargas, 2017; Ferreira et al., 2022). The decline in soil organic matter (SOM) and the intensification of erosion processes are largely attributed to unsustainable agricultural practices, vegetation clearance, increased frequency and intensity of droughts and floods, and forest fires (Karlen and Rice, 2015). In Mediterranean regions, these issues are exacerbated by intensive farming systems and adverse climatic conditions, such as water scarcity, which collectively contribute to soil degradation and the depletion of organic carbon

(Ferreira et al., 2022; Rodrigues et al., 2024). Given the central role of SOM in maintaining soil structure and nutrient availability for both soil biota and plants, its depletion leads to reduced soil fertility, negatively impacting biodiversity and plant productivity (Turbé et al., 2010).

Water availability is a major limiting factor in Mediterranean environments, and climate models predict a further reduction in precipitation across the region (Eekhout et al., 2025). Additionally, soil salinization poses a significant threat, driven by the region's semi-arid to arid climate, high evaporation rates, and historical land use practices, all of which contribute to excessive salt accumulation in soils (Salem and Jia, 2024). Elevated salinity levels adversely affect the physical and chemical properties of soils, as well as their microbiological functions

\* Corresponding author.

E-mail address: [mariaisabel.noguesgonzalez@cnr.it](mailto:mariaisabel.noguesgonzalez@cnr.it) (I. Nogues).

<https://doi.org/10.1016/j.jenvman.2025.126935>

Received 19 May 2025; Received in revised form 25 July 2025; Accepted 7 August 2025

Available online 9 August 2025

0301-4797/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

(Wang et al., 2024; Daba, 2025). In this sense, *Rosmarinus officinalis* L., an evergreen shrub native to the Mediterranean basin and a member of the Lamiaceae family, offers a promising solution to the challenges of soil degradation and drought. This species demonstrates notable resilience to harsh environmental conditions, including drought stress, which it mitigates through stomatal regulation during daylight hours and the activation of photoprotective and antioxidant mechanisms (Munné-Bosch and Alegre, 2000). Additionally, rosemary exhibits a degree of salt tolerance, attributed to its ability to regulate stomatal closure and initiate osmotic adjustments (Tounekti et al., 2008). The leaves of rosemary emit and store monoterpenes, a class of biogenic volatile organic compounds (BVOCs) with key ecological and physiological functions. In this species, monoterpene emission is primarily driven by diffusion from storage pools (Schurgers et al., 2009), although de novo synthesis in photosynthetic tissues also contributes to total emissions (Ormeño et al., 2009).

On the other hand, the improvements in waste collection and management systems favor the transition to a circular economy, improving the sustainability of these systems (Rahman et al., 2023). This change has led to the emergence of decentralized waste management models, such as agro-composting, community composting and decentralized urban composting, which enable localized, small-scale treatment very close to the source. Agrocomposting, which can be carried out on a small or medium scale, is a localized composting model that manages the organic wastes mainly from the agroindustrial and livestock sectors, close or even in the place where these wastes have been produced (Valverde-Orozco et al., 2024; Mira-Urios et al., 2025). Whereas that municipal waste, such as the organic fraction of municipal solid waste (OFMSW) is managed with the composting models of community composting, conducted by a community, and decentralized urban composting, carried in small-scale plants (Álvarez-Alonso et al., 2024).

The application of organic amendments such as compost has been shown to improve soil structure, enhance water infiltration and retention, and stimulate microbial respiration and enzymatic activity (Gajalakshmi and Abbasi, 2008). Moreover, compost serves as a nutrient source, a topic extensively explored in the literature (Hernández et al., 2016; García-López and Horta, 2022; Zapata-González et al., 2023). However, the benefits of compost are not immediate, as it releases nutrients gradually, requiring time for its effects to manifest (Alburquerque et al., 2011). Compost also supplies both macro- and micronutrients, thereby promoting plant growth and enhancing resilience under drought or saline conditions (Suvendran et al., 2025).

In this context, compost application has been demonstrated to improve soil quality and fertility by increasing SOM content. This sustainable strategy helps restore degraded soils by improving structure, enriching nutrients, and boosting microbial and enzymatic activity. (Filcheva and Tsadilas, 2002; Melero et al., 2007; Bustamante et al., 2012).

Savy et al. (2022) reported that compost application mitigated salt stress in tomato plants more effectively than mineral fertilisation. While salt stress reduced plant growth overall, compost-treated plants showed better tolerance, with more biomass and nutrients than those given mineral fertilisers. Similarly, Alsadon et al. (2024) observed that compost improved leaf gas exchange in plants, regardless of irrigation regime. Under drought conditions, plants grown in compost-amended soils showed greater biomass accumulation than those in untreated soils. In this sense, the effects of municipal waste-derived composts from decentralized composting scenarios on the soil plant system have been scarcely studied. Thus, Álvarez-Alonso et al. (2025) studied the effects of municipal solid waste-derived compost from decentralized composting scenarios (community and decentralized urban small-scale plants) in the soil and plant characteristics during two successive growing cycles of lettuce. Thus, there is an important lack of information concerning not only the effects of the composts produced in decentralized composting scenarios on the soil-plant systems, but mainly on the effects on the plant tolerance to different stress conditions.

Therefore, the goals of this study were: i) to assess whether the addition of composts from decentralized composting scenarios to a degraded soil can mitigate the stress experienced by the Mediterranean shrub *R. officinalis* under conditions of drought or salinity; ii) to evaluate the changes in monoterpene emission rates of rosemary plants, in response to increasing drought stress and fertilization with the composts from these specific composting models.

## 2. Materials and methods

### 2.1. Origin and characteristics of the soil and of the organic amendments

The soil utilized in this experiment was obtained from a former agricultural area that had been abandoned in the vicinity of Monterotondo (Rome, Italy). The requisite quantity of soil was collected from the topsoil (up to 20 cm deep), following the removal of all vegetation, roots, and stones. The soil was then left to dry in the open air. The soil type was identified as a clay-loam, exhibiting an alkaline pH of 8.43, with low electrical conductivity ( $0.25 \text{ mS cm}^{-1}$ ), and low concentrations of total nitrogen (1.26 g/kg dry soil), total organic carbon (0.83 %), and ammonium (0.002 g/kg dry soil) and nitrate (0.015 g/kg dry soil).

The soils were amended with eight composts obtained from different decentralized composting scenarios: two from community composting, two from decentralized urban composting, two from medium-scale agrocomposting (composting capacity approx. 20–200 t waste/year) and two from small-scale agrocomposting (composting capacity approx. 1000–2000 t waste/year). The composts from the community composting model (CA and FO) were produced in two different composting areas from two municipalities located at the Valencian Community (Spain); the composts from the decentralized urban composting (SO and JO) were produced at two small-scale decentralized urban composting plants located in Catalonia and Navarre, respectively. In both models (community and decentralized urban composting), the composts were obtained mainly from the organic fraction of selectively collected municipal waste, together with pruning waste, in a ratio of 1:1 (v:v). Specifically, in the case of the CA compost, the initial composting mixture contained 10 % fresh weight of donkey manure. On the other hand, the composts from medium-scale agrocomposting (TO and QU) consisted mainly of a mixture of olive pomace (oil mill waste) with prunings and pig slurry (TO) and olive leaves, poplar waste and chicken manure (QU) and were obtained in two installations (TO and QU) also located in the Valencian Community. In contrast, the composts from small-scale agrocomposting (UP and TI) were one obtained from chicken manure mixed with barn waste (UP), produced at a small composting module located in Navarre, while the other compost (TI) were produced in an area located in a livestock farm at the Valencian Community. The primary agronomic characteristics of the various composts utilized are delineated in Table 1. All composts were stable according to the Dewar test (Brinton et al., 1995), showed germination index values above 50 %, as described by Zucconi et al. (1981), which indicates the absence of phytotoxicity, and the values of macro and micronutrients, as well as the concentrations of heavy metals, were within the ranges considered normal for this type of compost (Álvarez-Alonso et al., 2024).

### 2.2. Experimental set up

In order to circumvent unfavourable atmospheric phenomena such as rainfall and substantial thermal variations, the experiment was conducted under greenhouse conditions at the CNR research (Montelibrètti, Rome, Italy). Two experiments were conducted in parallel: the first experiment investigated two factors, drought and organic amendment, while the second experiment focused on salinity and organic amendment. In both cases, polyethylene pots were filled with 700 g of soil, and five treatments were performed for each experiment (two composts from community composting, one compost from small-scale agrocomposting, one compost from medium-scale agrocomposting and one control

**Table 1**

Main agronomic characteristics of the compost treatments used in the experiment. Data are expressed as mean value  $\pm$  standard deviation in dry weight basis. EC: electrical conductivity, OM: organic matter, TN: total nitrogen, P: phosphorous, K: potassium, CA and FO: community composting composts, SO and JO: decentralized urban composting composts, UP and TI: small-scale agrocomposting composts, TO and QU: medium-scale agrocomposting composts. Mean values followed by the same letter are not significantly different at  $p < 0.05$  (Tukey test).

Parameters	CA	SO	UP	TO	FO	JO	TI	QU
Moisture (%)	43.8 c $\pm$ 0.7	43.7 b $\pm$ 2.3	32.2 b $\pm$ 0.4	45.3 a $\pm$ 0.6	28.3 c $\pm$ 1.9	46.9 c $\pm$ 6.2	40.6 c $\pm$ 3.3	12.0 c $\pm$ 0.2
pH	8.6 d $\pm$ 0.1	8.0 c $\pm$ 0.1	7.2 a $\pm$ 0.1	7.0 a $\pm$ 0.1	8.1 c $\pm$ 0.1	7.6 b $\pm$ 0.1	8.2 c $\pm$ 0.1	9.0 e $\pm$ 0.1
EC (mS cm <sup>-1</sup> )	6.07 e $\pm$ 0.13	5.19 d $\pm$ 0.11	10.48 f $\pm$ 0.14	5.22 d $\pm$ 0.15	3.20 b $\pm$ 0.09	1.12 a $\pm$ 0.02	3.83 c $\pm$ 0.09	3.31 e $\pm$ 0.04
OM (%)	37.8 ab $\pm$ 0.5	56.2 c $\pm$ 0.9	73.8 f $\pm$ 0.9	62.6 e $\pm$ 1.0	38.2 b $\pm$ 0.5	40.8 c $\pm$ 0.8	35.8 a $\pm$ 0.9	60.4 e $\pm$ 0.8
Ratio C/N	11.9 b $\pm$ 1.4	11.0 d $\pm$ 2.0	14.7 c $\pm$ 1.3	15.3 e $\pm$ 1.4	13.3 a $\pm$ 2.1	13.0 d $\pm$ 1.3	10.7 c $\pm$ 1.6	16.5 a $\pm$ 1.4
Humic acid (%)	5.13 d $\pm$ 0.08	10.72 f $\pm$ 0.35	7.73 e $\pm$ 0.10	3.41 bc $\pm$ 0.06	2.79 a $\pm$ 0.04	2.93 ab $\pm$ 0.19	3.46 c $\pm$ 0.19	7.53 e $\pm$ 0.22
Fulvic acid (%)	1.46 b $\pm$ 0.02	2.38 d $\pm$ 0.06	2.81 e $\pm$ 0.05	1.29 a $\pm$ 0.02	1.21 a $\pm$ 0.02	1.28 a $\pm$ 0.04	1.60 bc $\pm$ 0.02	1.73 c $\pm$ 0.13
TN (%)	2.11 c $\pm$ 0.03	2.85 e $\pm$ 0.06	2.49 d $\pm$ 0.03	2.20 c $\pm$ 0.03	1.76 a $\pm$ 0.02	1.89 b $\pm$ 0.03	1.89 b $\pm$ 0.01	2.15 c $\pm$ 0.03
P (g kg <sup>-1</sup> )	7.5 b $\pm$ 0.1	9.5 c $\pm$ 0.1	11.7 d $\pm$ 0.3	23.7 e $\pm$ 1.4	9.1 c $\pm$ 0.1	6.3 b $\pm$ 0.2	3.9 a $\pm$ 0.1	4.8 a $\pm$ 0.1
K (g kg <sup>-1</sup> )	20.7 e $\pm$ 0.3	11.1 b $\pm$ 0.2	33.4 f $\pm$ 1.0	14.0 c $\pm$ 1.5	8.8 a $\pm$ 0.3	7.1 a $\pm$ 0.1	16.6 d $\pm$ 0.2	16.6 d $\pm$ 0.2

treatment, without amendment). A standardized dose of 210 kg N ha<sup>-1</sup> year<sup>-1</sup>, considering the rosemary requirements and the maximum N application rate according to the EU Nitrate Directive, was applied in each treatment except the control, exactly 19.7 g/kg soil for TO; 20.0 g/kg soil for CA; 23.5 g/kg soil for FO; 15.0 g/kg soil for SO; 22.1 g/kg soil for JO; 19.1 g/kg soil for QU; 21.9 g/kg soil for TI and 17.5 g/kg soil for UP. The compost was incorporated and mixed superficially. Six replicates were conducted for each treatment, yielding 30 experimental pots for each experiment (drought and salinity) and a total of 60 pots for both experiments. In each pot, a *Rosmarinus officinalis* cutting with 100 days of nursery growth (provided by Agraria Mentana, Mentana, Rome, Italy) was planted one week after the establishment of the fertilization treatment. Cuttings were 6–7 cm high. The pots were randomly distributed within the greenhouse. The pots were kept at 75 % of their maximum water holding capacity (WHC) and under the same natural temperature and light conditions until the start of treatments five weeks after rosemary planting. In the context of the drought experiment, the drought control pots (DC) were irrigated as usual to keep 75 % of the soil's WHC, while the drought stress pots (DS) were maintained at 20 % of WHC. To ensure the maintenance of these water conditions, the amount of water lost by each pot was monitored daily by weighing the pots and measuring the change in weight. In the salinity experiment, the salt control pots (SC) were irrigated with 50 mL of distilled water three times per week, while the salt stress pots (SS) were irrigated with a 150 mM NaCl solution (Tounekti et al., 2011). In order to prevent the plant from undergoing shock salt stress, the salt concentration of the irrigation water was increased during the week prior to stress application by performing 50 mL irrigations every other day and increasing the NaCl concentration from 50 mM, 100 mM and 150 mM.

### 2.3. Gas exchange measurement, VOC emission and reflectance determination

Gas exchange and reflectance measurements were performed at three points during the experiment: days 0, 15 and 30, with day 0 designated as the beginning of the treatment (drought or salinity).

Net photosynthetic rates (A), stomatal conductance (gs) and transpiration (E) were measured using LI-6800 IRGA with a 6800-13 large leaf chamber and a 6800-03 light source (LI-COR Biosciences Inc., Lincoln, NE, USA). Experimental conditions were set as follows: PAR at 500  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , temperature at 25 °C, CO<sub>2</sub> concentration at 430 ppm, relative humidity at 50 %, and airflow at 400  $\mu\text{mol s}^{-1}$ . Data were recorded once the gas exchange stabilized. Gas exchanges were measured on all plant's main branch between 10.00 and 16.00 h (solar time). Gas exchange parameters depend on the sampled leaf area. Since it was not possible to detach the needles at each measurement point during the experiment, we developed a model to correlate needle length with needle area. We collected 100 needles from plants excluded from the experiment and measured their length and area by scanning them on

black paper alongside a ruler, then calculating the area using ImageJ software. Based on these measurements, we developed a mathematical model (second degree equation,  $R^2 = 0.7056$ ) to relate needle length to area. This model was then used to estimate leaf area by measuring the length of each needle at each time point.

After gas exchange measurements, the same branches were utilized for the collection and subsequent measurement of monoterpene emissions. Volatile organic compounds (VOCs) were sampled from the plant's main branch using an LI-6400XT gas analyzer equipped with a 6400-05 conifer chamber (LI-COR Biosciences Inc., Lincoln, NE, USA). Chamber conditions were standardized to ensure accurate comparisons between treatments. PAR was set to 1000  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , temperature to 30 °C, CO<sub>2</sub> concentration to 430 ppm, and airflow to 500  $\mu\text{mol s}^{-1}$ . Relative humidity inside the chamber ranged between 45 % and 55 %. The laboratory's atmospheric pressure during measurements was approximately 100.8 kPa. A sorbent tube filled with 200 mg of Tenax was connected to the chamber outlet via 1/4" internal diameter FEP tubing. Air exiting the chamber was sampled at a constant rate of 200 mL min<sup>-1</sup> using a Pocket Pump TOUCH Sample Pump (SKC Ltd., Dorset, UK), with a total sample volume of 3.0 L per sample. To prevent potential VOC contamination from the laboratory, a Supelco Supelpure hydrocarbon trap was connected to the LI-6400XT inlet. Sampling began once the gas exchange reached a steady state, defined as a CO<sub>2</sub> differential coefficient of variation below 1 %, typically reached within 3 min.

The collected tubes were desorbed using a TD-100XR thermal desorber (Markes International Limited, Llantrisant, UK). The released compounds were then detected by gas chromatography-mass spectrometry (GC-MS) (GCMS 8860-5977C, Agilent Technologies, Wilmington, USA), equipped with a 20 m long HP-5MS Ultra Inert capillary column (inner diameter: 0.18 mm; J&W Scientific USA, Agilent Technologies, Palo Alto, CA, USA). The oven temperature was programmed as follows: 3 min at 35 °C, followed by an increase of 3 °C min<sup>-1</sup> to 50 °C, and then 5 °C min<sup>-1</sup> up to 250 °C, which was held for 5 min. We used hydrogen produced by an HG PRO LN PEM generator (LNI Swissgas SA, Switzerland) as the carrier gas. The GC-MS was calibrated by sampling different VOC concentrations obtained by diluting a standard gas with pure nitrogen (S.I.A.D. S.p.A., Italy). Chromatographic data were analyzed using Agilent MassHunter Workstation Qualitative Analysis 10.0 (Agilent Technologies, Wilmington, USA).

Reflectance measurements were performed using an ASD FieldSpec 4 Hi-Res spectroradiometer (Analytical Spectral Devices Inc., USA). The instrument operates across the 350–2500 nm spectral range, with an average spectral resolution of 3 nm (full width at half maximum, FWHM) and a sampling interval of 1.4 nm in the visible range, and a spectral resolution of 8 nm with a sampling interval of 1.1 nm in the SWIR range. A Spectralon white reference panel was used as a reflectance standard before each measurement. Each measurement consisted of the average of 20 instrument scans. Reflectance spectra were pre-processed using ViewSpecPro (ASD) software. Measurements were

taken from above the canopy of each plant at a distance of 5 cm. Reflectance indices such as NDVI, PRI, PSRI, TCARI, CRI, and MCARI1 were calculated following the approach described by Nestola et al. (2018), while PSSR<sub>a</sub> index was calculated as described by Pietrini et al. (2023).

#### 2.4. Analytical determinations

Plant samples were collected at the end of the greenhouse experiments (after one month of stress application). The rosemary plants were meticulously extracted from their pots and thoroughly rinsed with distilled water to ensure the removal of any adhering particles. Their fresh weight was then determined by weighing both the aerial parts and the roots. The plants were then dried at 60 °C in an air-forced oven and 72 h after their dry weights were determined. Plant material was then grinded to analyze its nutritional content, including macro and micro-nutrients, as well as the presence of heavy metals (ICP) and C and N content. Leaf C and N content were analyzed by dry combustion at 950 °C using an elemental analyzer (Truspec CN, Leco, St. Joseph, MO, USA). Total P, K, Ca, Mg, Na and heavy metals (Fe, Cd, Cu, Mo, Ni, Pb, Zn, Mn) in leaves were determined in the extract obtained after digestion with a mixture of hydrogen peroxide and nitric acid (H<sub>2</sub>O<sub>2</sub> – HNO<sub>3</sub> 1:4, v:v) by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Shimadzu 9000). All analyses were conducted on three samples per treatment group (n = 3).

At the commencement of the experiment soil was permitted to desiccate in the open air for the purpose of subsequent physico-chemical and chemical characterization. The electrical conductivity (EC) and pH of the soils were determined in aqueous extracts prepared at a ratio of 1:5 (w/v) and 1:2.5 (w/v), respectively, using a pH/EC meter (Crison Instruments, S.A., Barcelona, Spain) according to the standardized method described in DIN EN 12176, 1998. Total organic matter (TOM) and total organic carbon (TOC) were determined according to the modified Walkley and Black method (Yeomans and Bremner, 1988). The water-soluble carbon (WSC) fraction of the soil was determined in a 1:20 (w/v) aqueous extract using an automated carbon analyzer (TOC-VCSN, Shimadzu Corporation, Kyoto, Japan). Total Kjeldahl nitrogen (TKN) was determined according to the method described by Bremner and Britebeck (1983), and the nitrate (NO<sub>3</sub><sup>-</sup>-N) and ammonium (NH<sub>4</sub><sup>+</sup>-N) forms were quantified using a K-365 Dist Line multiparameter analyser (BÜCHI Labortechnik AG). The concentration of these forms was determined in a 0.2 M KCl 1:5 (w/v) extract using the MgO-Devarda alloy steam distillation method (Bremner and Keeney, 1965). All analyses were carried out in triplicate.

The relative water content (RWC) of rosemary leaves from each treatment was determined using the following formula:

$$\text{RWC (\%)} = ((\text{FW} - \text{DW}) / (\text{TW} - \text{DW})) \times 100 \quad (1)$$

In order to ascertain the fresh weight (FW) of the plants, three leaves from each plant were immediately weighed. The leaves were then immersed in distilled water for a period of 24 h. After 24 h the leaves were removed, passed through blotting paper to absorb water from the surface, and weighed again to obtain the turgid weight (TW). Thereafter, they were subjected to an oven temperature of 50 °C for a duration of 48 h, in order to determine their dry weight (DW).

#### 2.5. Statistical analysis

The normality of the results of all the parameters was evaluated using the Shapiro-Wilk test. Subsequently, the results on compost parameters, nutritional content of rosemary plants, dry biomass and total monoterpene emission were evaluated by one-way ANOVA and, to determine the significance of the differences observed between means, a post-hoc analysis was performed using Tukey's test, with a p-value <0.05. The Infostat program version 2020 for Windows was used for all

statistical analysis.

A Two-Way MANOVA was conducted to explore the combined effects of substrate with either drought or salt stress (at the end of the experiment) via IBM SPSS v. 29.0.1.0 (171), specifically for pigment indexes (i.e., NDVI, PRI, PSRI, TCARI, CRI and MCARI1) and VOC emission. Post-hoc contrast was carried out by Tukey HSD (p < 0.05).

### 3. Results and discussion

#### 3.1. Environmental data and stress indicators

Mean temperature inside the greenhouse ranged from 19.5 °C at the beginning of the experiment (drought and salinity) to 13.5 °C at its conclusion. Daytime length was 10 h 19 min at the beginning of the stress application and 9 h 14 min at the end. Fig. 1 shows the temperature and humidity values inside the greenhouse during the experiment.

Leaf RWC was determined in all plants at the end of both stresses, drought and salinity. The leaf relative water content (RWC) decreased with the drought and salt stress treatments from 86.6 ± 3.3 (mean ± SD) (non-stressed plants) to 51.14 ± 15.3 and 75.6 ± 2.2 (stressed plants), respectively. No significant differences in the RWC were observed among plants cultivated in the various amended soils (data not shown).

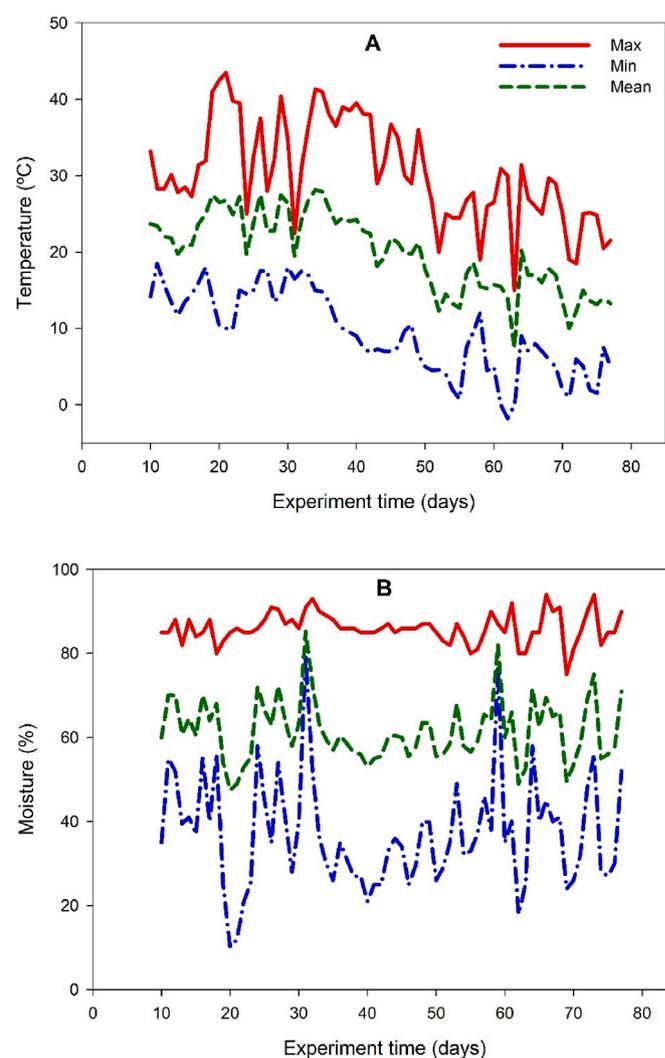


Fig. 1. Evolution of temperature (A) and moisture (B) inside the greenhouse during the experimental time.

3.2. Plant biomass and leaf nutrient contents

Statistical differences in rosemary leaf nutrients were found following the application of diverse stresses and treatments, except for Zn in non-drought (DC) and K under salt stress (SS) (Table 2). In drought trials, TN, P, and K levels rose with all composts compared to untreated plants, regardless of the irrigation conditions to which they were subjected. On the other hand, K content in rosemary plants increased under drought stress conditions (DS) across all compost treatments compared to DC (Table 2). Kamanga et al. (2024) found that water-stressed lettuce had higher leaf K, linking it to K role in osmotic regulation. We also observed increased Na, Cu, Mg, Mn, and Zn in leaves (Table 2), consistent with osmotic adjustment reported by Kamanga et al. (2024). Leaf Na content increase because of drought was higher in SO and TO plants than in any of the other treatments. TO and C plants showed more Na, Mg, and K likely due to concentration effects as biomass declined under drought (Fig. 2). The dynamics observed in the salinity experiment are distinct from those previously mentioned. TN concentrations in QU were found to be lower than in the rest of the treatments, comprising C, when well-irrigated, but when salinity conditions were applied, TN values in QU remained in the range of C. In contrast, in the rest of the treatments, TN values increased with regards to C. In both instances SS and salt control pots (SC), the leaves from TI plants exhibited higher P levels in comparison to those from C plants. In relation to leaf K concentrations, it was observed that only QU leaves exhibited higher levels of leaf K than those of C in SC pots. The application of NaCl-based saline irrigation resulted in elevated Na concentrations in the SS treatment, in comparison to SC conditions. Indeed, plants respond to salt stress by osmotic adjustment, generally by increasing the concentration of Na<sup>+</sup> and Cl<sup>-</sup> in their tissues. Excess ion accumulation due to salt stress may harm cells and disrupt physiology, inducing leaf damage (Tounekti et al., 2011; Acosta-Motos et al., 2017). In this context, no effects associated with high toxicity symptoms were observed in the present study. Moreover, ion imbalances can occur by excessive uptake of Na<sup>+</sup>. Competition between cations can result to some nutrient deficiency in plants. In our study, concomitant to the Na increase, we observed a decrease in leaf K levels in all treatment with the

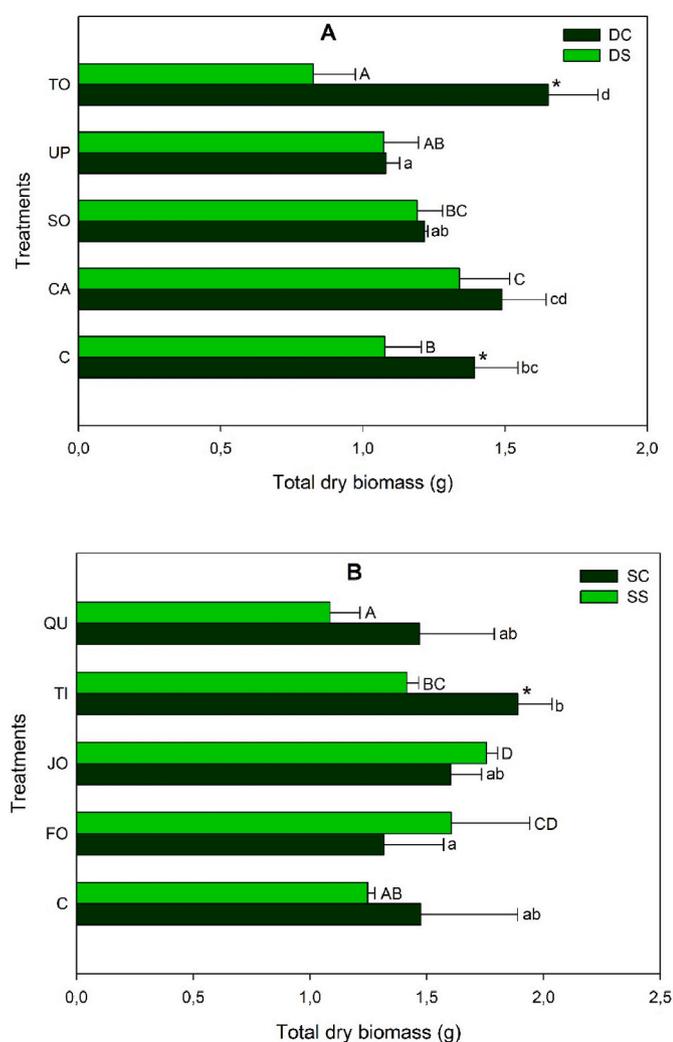
exception of FO, an increase in leaf Ca levels in all treatments except in JO and a decrease in Mg levels in FO and QU leaves. Furthermore, it has been documented that high K<sup>+</sup>/Na<sup>+</sup> selectivity under saline conditions is regarded as one of the pivotal selection criteria for salt tolerance in plants (Ashraf and Harris, 2004). As Tounekti et al. (2008) indeed asserted, the maintenance of a higher K<sup>+</sup>/Na<sup>+</sup> ratio within the leaves could be considered a significant component of the salt-tolerance strategy exhibited by rosemary. In this study, FO and TI leaves exhibited elevated K/Na ratios (3.91 and 3.54, respectively) in comparison to C (3.18). In contrast, JO and QU leaves presented lower K/Na ratios (2.21 and 3.09, respectively) than C leaves.

Concerning rosemary plant biomass, statistically significant differences were observed among the different compost treatments studied in both experiments (p < 0.05). In the context of drought experiment (Fig. 2A), under well-watered conditions (DC) total dry biomass resulted to be 1.9-, 1.35- and 1.53-fold higher in plants grown in TO composted amended soils than in C, SO and UP, respectively. The higher biomass in TO plants may be due to the higher P levels in TO compost with regard to other ones (23.7 ± 0.98 g/kg in TO, 7.5 ± 0.09 g/kg in CA, 9.5 ± 0.09 g/kg in SO, and 11.7 ± 0.2 g/kg in UP, respectively). Also, leaf phosphorus (P) levels were higher in plants from the TO treatment than in those from the other treatments (Table 2) in DC and DS conditions. CA also showed higher biomass than C, likely because both composts contained manure. Kamanga et al. (2024) also observed superior lettuce yield results in treatments with compost from co-composting of market waste and sewage sludge versus compost from market waste alone. Conversely, SO and UP treatments had lower biomass than C, possibly due to slow mineralization limiting nutrient availability (Geisseler et al., 2024). Furthermore, the elevated electrical conductivity of UP compost (Table 1) is indicative of a high salt concentration, which has the potential to exert a detrimental effect on plant growth (Atiyeh et al., 2001). The impact of drought stress on plant biomass was investigated, with the results indicating a significant reduction in both C (29 % reduction) and TO (50 % reduction) treatments when compared to well-watered plants (Fig. 2A). Biomass loss in TO-treated plants under drought may be due to its lower humic acid content in comparison to other compost types (Table 1). Interestingly, the biomass of TO plants was the lowest among

Table 2

Leaf concentration of total N (%), P (mg kg<sup>-1</sup>), K (mg kg<sup>-1</sup>), Na (mg kg<sup>-1</sup>), Ca (mg kg<sup>-1</sup>), Mg (mg kg<sup>-1</sup>), Mn (mg kg<sup>-1</sup>), Fe (mg kg<sup>-1</sup>), Cu (mg kg<sup>-1</sup>) and Zn (mg kg<sup>-1</sup>) in *Rosmarinus officinalis* plants grown on the different treated soils after application of drought (DS), salinity stress (SS) or under control conditions (DC and SC for drought and salinity experiment, respectively). Data are expressed as mean value in dry weight basis (n = 3). Different lowercase letters indicate significant differences among fertilization treatments in control conditions (p < 0.05). Different capital letters indicate significant differences among fertilization treatments under stress conditions (p < 0.05). Asterisks indicate significant differences between stressed and non-stressed plants (p < 0.05).

Parameters	Treatments	C	CA	SO	UP	TO	C	CA	SO	UP	TO
	Experiment	DC					DS				
TN (%)	Drought experiment	1.75a	2.33bc	2.22b	2.43c	2.3bc	1.73A	2.17C*	2.00B*	2.13C*	2.26D*
P (mg kg <sup>-1</sup> )		1731a	1888b	1873b	1844b	2287c	1735A	1896B	1914B	1922B	2171C
K (mg kg <sup>-1</sup> )		23997a	24443a	25073a	26820b	24889a	24780A*	25656AB	26620B*	28539C*	31037D*
Na (mg kg <sup>-1</sup> )		851a	1028c	908 ab	915b	892 ab	1253A*	1472B*	1805D*	1278A*	1706C*
Ca (mg kg <sup>-1</sup> )		11283c	9659a	11102c	12670d	10304b	10127B*	9912B	11524C*	13014D	8980A*
Mg (mg kg <sup>-1</sup> )		2122a	2145 ab	2289b	2306b	2692c	2222A*	2340B	2678C*	2676C	3055D*
Mn (mg kg <sup>-1</sup> )		49.6b	47.5a	52.3b	62.0d	58.2c	48.6A	49.9A	58.4B	66.3C*	58.0B
Fe (mg kg <sup>-1</sup> )		390c	148a	303b	333bc	169a	318C	254B*	374D*	432E	180A*
Cu (mg kg <sup>-1</sup> )		104b	93a	116c	93a	124d	86A*	101B*	114C	116C*	161D*
Zn (mg kg <sup>-1</sup> )		101a	61a	75a	72a	83a	60A	69AB*	76BC	84BD	91D*
Parameters	Treatments	C	FO	JO	TI	QU	C	FO	JO	TI	QU
Experiment	SC						SS				
TN (%)	Salinity experiment	2.16b	2.13b	2.14b	2.33b	1.62a	1.86A*	2.15BC	2.09B	2.21C*	1.85A*
P (mg kg <sup>-1</sup> )		1905c	2031d	1790b	1996d	1690a	1448AB*	1476B*	1421AB*	1569C*	1389A*
K (mg kg <sup>-1</sup> )		25356bc	23443a	24612 ab	25132bc	26209c	22960A*	23429A	22368A*	22830A*	23539A*
Na (mg kg <sup>-1</sup> )		921b	1196d	1077c	818a	945b	7223C*	6000A*	10125D*	6457B*	7283C*
Ca (mg kg <sup>-1</sup> )		9569a	12959d	11123b	12906d	12323c	19214D*	14173B*	11533A	17249C*	13836B*
Mg (mg kg <sup>-1</sup> )		2191b	2360c	2051a	2300bc	1931a	2100C	2091C*	1967B	2119C*	1832A
Mn (mg kg <sup>-1</sup> )		48.6 ab	55.2c	47.9a	49.8 ab	51.3b	60.6B*	50.9A*	48.5A	57.5B*	49.1A
Fe (mg kg <sup>-1</sup> )		209a	495c	296b	314b	480c	802E*	375B*	231A*	549D*	451C
Cu (mg kg <sup>-1</sup> )		78b	62a	83c	65a	103d	106B*	75A*	105B*	83A*	102B
Zn (mg kg <sup>-1</sup> )		89d	57a	59a	63b	72c	66B*	62A*	69B*	66AB*	69B



**Fig. 2.** Dried biomass of rosemary after application of drought (A) and salt (B) stresses. Data values reported as average per treatment  $\pm$  standard deviation ( $n = 3$ ). Different lowercase letters within a column indicate significant differences among no stress treatments (DC and SC) and different capital letters within a column indicate significant differences among stressed treatments, drought (DS) or salt stress (SS) ( $p < 0.05$ ). Asterisks indicate significant differences between same treatment stressed and unstressed. For other abbreviations see Tables 1 and 2

all droughted plants, comprising C plants. Humic substances can help plants to withstand abiotic stresses (Khorasani et al., 2023; Aly et al., 2024). On the contrary, CA plants presented a higher biomass than C plants under drought conditions (Fig. 2A). In their study, Formica et al. (2024) observed that the imposition of drought conditions during the balsamic period of rosemary growth did not impact dry biomass production.

In relation to the salinity experiment, the TI plants exhibited the highest level of biomass when irrigated with normal water (Fig. 2B). Salt stress reduced biomass by 27 % in TI and 26 % in QU compared to their well-watered counterparts. Similarly to what was observed in the present study, Acosta-Motos et al. (2017) reported a general reduction in dry biomass in different types of plants subjected to salinity stress. Moreover, under salt stress conditions, FO and JO plants exhibited higher biomass compared to C plants (Fig. 2B) whereas QU presented the lowest biomass. Choi et al. (2024) found humic substances improved spinach growth under salt and drought stress in a greenhouse. However, no differences were observed between the biomass of the treatments and the control when the plants were also subjected to daily heat stress High

greenhouse temperatures early in the study may have caused heat stress, lessening compost benefits under salt stress.

### 3.3. Gas exchange measurements and estimation of leaf chlorophyll content

Photosynthetic rates (A) were similar across treatments at the start of the drought experiment (range 3.5–5.7  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ). A Two-way ANOVA analysis showed not statistical differences among fertilization treatments (fertilization factor  $P = 0.419$ ), and between control and drought plants (drought factor  $P = 0.129$ ).

Stomatal conductance values at T0 were also similar across all compost treatments (0.035–0.098  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), (fertilization factor  $P = 0.527$ , drought factor  $P = 0.093$ ). At the same time, to monitor the changes in the leaf chlorophyll content, the pigment-specific simple ratio index (PSSR<sub>a</sub>) was measured. The PSSR<sub>a</sub> index is used to estimate leaf chlorophyll content, particularly in situations where vegetation is stressed (Li et al., 2023). The results of PSSR<sub>a</sub> were in line with the gas exchange measurements showing no significant differences between the treatments at the beginning of the experiment (fertilization factor  $P = 0.206$ , drought factor  $P = 0.382$ ). Nevertheless, the level of A dropped significantly in drought-stressed plants compared to controls at both 15 and 30 days ( $P < 0.001$ ). (Table 3). A was 2.3 and 7.2-fold lower in DS plants than in DC ones at 15 days and at 30 days, respectively ( $P < 0.001$ ). Drought also decreased stomatal conductance in all amendment treatments at 15 ( $P < 0.001$ ) and 30 days ( $P < 0.001$ ) (Table 3). Moreover, no differences were observed among the various fertilization treatments with respect to the A, gs and PSSR<sub>a</sub> values at T15 (A:  $P = 0.254$ ; gs:  $P = 0.104$ ; PSSR<sub>a</sub>:  $P = 0.197$ ) and T30 (A:  $P = 0.583$ ; gs:  $P = 0.410$ ; PSSR<sub>a</sub>:  $P = 0.242$ ). On the other hand, a significant reduction in chlorophyll content was only observed after 30 days ( $P < 0.001$ ).

In the study by Jamaladdeen et al. (2023), it was reported that the cell walls and leaves of rosemary officinalis exhibited anatomical changes after a period of 16 days of drought, resulting in a leaf water loss of 15.5 %. These anatomical changes have been shown to limit non-stomatal transpiration as well as CO<sub>2</sub> diffusion. Furthermore, a significant decline in chlorophyll content was observed in

**Table 3**

Net photosynthetic rates ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), stomatal conductances ( $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and pigment-specific simple ratio index (PSSR<sub>a</sub>) throughout the experiment for control, drought and salinity stressed rosemary plants. Mean values  $\pm$  standard deviation are shown ( $n = 15$ ). Asterisks indicate significant differences between well-watered (DC and SC) and drought (DS) or salt stress (SS) plants at each measurement time (0, 15 and 30 days). For other abbreviations see Tables 1 and 2

Time	Treatment	A ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )	gs ( $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ )	PSSR <sub>a</sub>
<i>Drought experiment</i>				
0 days	DC	5.2 $\pm$ 2.0	0.076 $\pm$ 0.048	7.25 $\pm$ 1.04
	DS	4.7 $\pm$ 1.7	0.053 $\pm$ 0.042	6.89 $\pm$ 1.20
	(p)	0.129	0.093	0.382
15 days	DC	5.2 $\pm$ 1.4	0.082 $\pm$ 0.029	7.26 $\pm$ 1.16
	DS	2.3 $\pm$ 1.2*	0.021 $\pm$ 0.017*	5.62 $\pm$ 2.32
	(p)	<0.001	<0.001	0.108
30 days	DC	4.3 $\pm$ 0.7	0.066 $\pm$ 0.022	8.78 $\pm$ 1.31
	DS	0.6 $\pm$ 0.5*	0.003 $\pm$ 0.001*	3.99 $\pm$ 1.40*
	(p)	<0.001	<0.001	<0.001
<i>Salinity experiment</i>				
0 days	SC	4.8 $\pm$ 1.4	0.073 $\pm$ 0.027	6.57 $\pm$ 1.25
	SS	5.0 $\pm$ 0.9	0.057 $\pm$ 0.026	6.66 $\pm$ 1.26
	(p)	0.743	0.095	0.844
15 days	SC	5.2 $\pm$ 0.9	0.082 $\pm$ 0.020	6.54 $\pm$ 1.27
	SS	2.5 $\pm$ 1.5*	0.017 $\pm$ 0.013*	6.81 $\pm$ 1.20
	(p)	<0.001	<0.001	0.557
30 days	SC	4.4 $\pm$ 0.9	0.079 $\pm$ 0.027	7.50 $\pm$ 1.67
	SS	2.0 $\pm$ 1.5*	0.020 $\pm$ 0.021*	7.07 $\pm$ 1.42
	(p)	<0.001	<0.001	0.455

drought-treated plants compared to those cultivated in well-watered conditions, attributed to an accumulation of dead cells.

Also, in the case of the salt stress experiment, no significant differences were observed in A values among the different fertilization treatments at T0 (range 4.2–5.6  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) (fertilization factor  $P = 0.426$ , salinity factor  $P = 0.743$ ) or gs values (0.037–0.094  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) (fertilization factor  $P = 0.059$ , salinity factor  $P = 0.095$ ) and PSSR<sub>a</sub> values (fertilization factor  $P = 0.197$ , salinity factor  $P = 0.844$ ). The results, shown in Table 3, demonstrated a significant decrease in A and gs levels with salt stress. Salt stress caused a significant drop in A (2–2.2 fold lower) and gs (4–4.82 fold lower) at 15 and 30 days ( $P < 0.001$ ), respectively. Moreover, no differences were observed among the various fertilization treatments with respect to the A, gs and PSSR<sub>a</sub> values at T15 (A:  $P = 0.175$ ; gs:  $P = 0.470$ ; PSSR<sub>a</sub>:  $P = 0.326$ ) and T30 (A:  $P = 0.561$ ; gs:  $P = 0.173$ ; PSSR<sub>a</sub>:  $P = 0.057$ ).

### 3.4. Monoterpene emission

In well-watered plants on unamended soil, the main monoterpenes emitted were  $\alpha$ -pinene (47.4 %), camphene (12.7 %), cineole (8.2 %),  $\beta$ -pinene (7.8 %), limonene (7.2 %), borneol (5.7 %), and myrcene (5.2 %). Other monoterpenes were linalool, terpinene, terpineol and verbenone. The only sesquiterpene we detected was  $\beta$ -cariophyllene.

Monoterpene emissions from well-watered DC and SC plants showed a slight, non-significant decrease over time (Fig. 3A and B), likely due to a decline in temperature (from 19.5 °C to 13.5 °C) and/or accumulative temperature (from 24.7 °C to 15.8 °C). Indeed, elevated temperatures enhance terpenoid emissions by increasing their volatility and stimulating biosynthesis through enzyme activity (Duan et al., 2019). Also,  $\beta$ -cariophyllene decreased throughout the experiment.

On the other hand, it was observed that there was a significant increase in monoterpene emission rates in SS plants in comparison to the SC plants at the beginning of the experiment (Fig. 3B). In this regard, we have to take into consideration that rosemary plants were irrigated with solutions of increasing salt concentrations during the week prior to the initial measurements. With drought, we also observed an increase in monoterpene emission rates at the beginning of the treatment though this increase was not significant (Fig. 3A). The hydration of the DC plants was conducted immediately prior to the commencement of measurements. In contrast, the DS plants had not been watered for a period of three days prior to the initiation of measurements. This was due to the necessity of ensuring that the soil attained a WHC of 20 % for its subsequent maintenance.

Other studies have also shown an increase in monoterpene emissions during the initial phase of stress application. Ormeño et al. (2007) observed in the first days of stress a positive effect of drought on monoterpene emissions of *P. halepensis*, a monoterpene storing species. Also, Nogués et al. (2015) observed the same behaviour with rosemary plants and drought. In relation to the impact of salt on BVOCs, Tomescu et al. (2017) reported the induction of monoterpene emissions in salt-stressed *Solanum lycopersicum*. Terpene storage pools can rapidly respond to stress, including salinity and drought, by releasing stored compounds without needing new synthesis or depending on photosynthesis (Byron et al., 2022). The increase in monoterpene emissions may be attributable to a number of factors. Contributing factors include higher temperatures from reduced evaporation due to stomatal closure, and the use of alternative carbon sources instead of newly fixed photosynthate for terpene production (Ormeño et al., 2007). Also, the expression of monoterpene synthases has been demonstrated to be subject to regulation by drought conditions and salt stress. For instance, in *Salvia officinalis*, sabinene synthase is shown to be overexpressed, whilst cineole synthase is found to be underexpressed in response to drought (Radwan et al., 2017). On the other hand, Valifard et al. (2018) found that the transcript of the cineole synthase gene accumulated in leaves of *Salvia mirzayanii* plants during the early hours of salinity treatment.

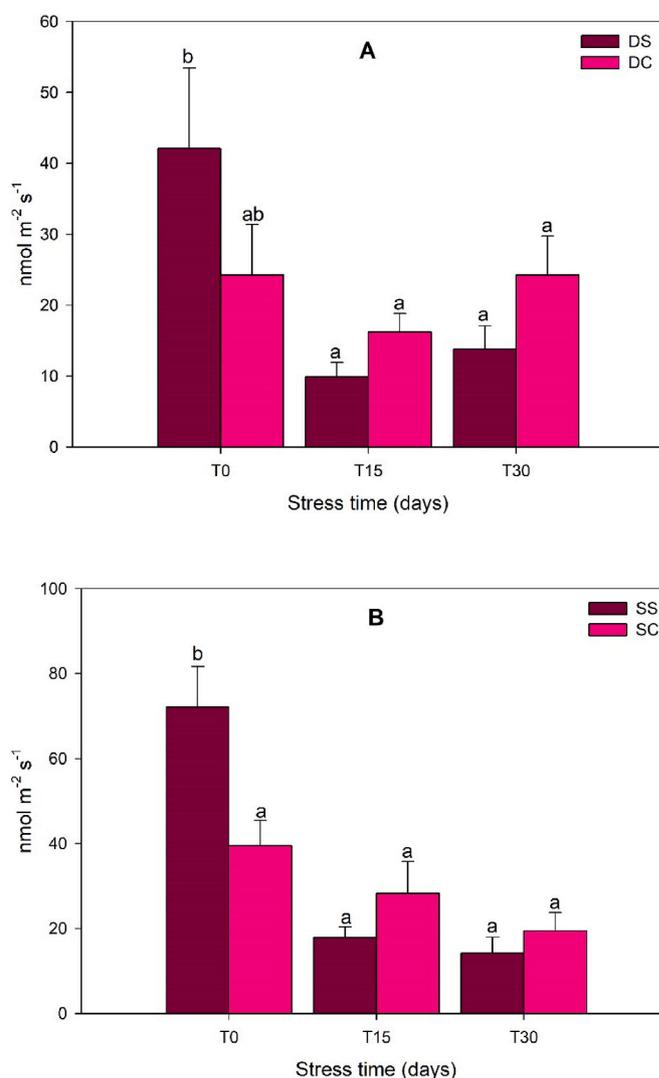


Fig. 3. Total monoterpene emissions rates ( $\text{nmol m}^{-2} \text{s}^{-1}$ ) during the drought experiment for well-watered (DC) and drought stress (DS) rosemary plants (A) and during the salinity experiment for well-watered (SC) and salt stress (SS) (B) rosemary plants. Mean values  $\pm$  standard deviation ( $n = 15$ ). Different letters indicate significant statistical differences ( $p < 0.05$ ).

These differences were not significant, except for non-oxygenated monoterpenes under drought at the third sampling ( $P = 0.041$ ), despite large reductions in both A and gs under salt and drought stress. A Two-Way MANOVA was conducted to explore the combined effects of compost and treatment (drought or salt stress) on oxygenated monoterpene or non-oxygenated monoterpene emissions at T30 (Table 4). In the drought experiment, non-oxygenated monoterpenes changed significantly with treatment ( $p = 0.041$ ) and with the interaction compost  $\times$  treatment ( $p = 0.025$ ). Nevertheless, oxygenated monoterpenes changed only with the interaction compost  $\times$  treatment ( $p = 0.011$ ). In the case of salinity, no differences were found in relation to compost and/or treatment (Table 4).

Early responses to water and salt stress are largely analogous (Munns, 2002). Drought and salinity have been shown to induce a physiological water deficit (Chaves et al., 2009). However, in the case of prolonged salt stress, plants exhibit a response to direct toxic effects of absorbed salt ions and osmotic stress (Chaves et al., 2009). In our study the effects of drought and salt stress with regards to gas exchange parameters and monoterpene emissions are similar though with some differences. Indeed, we have observed a strong positive correlation between leaf RWC and both oxygenated ( $P = 0.01$ ;  $R = 0.76$ ) and

**Table 4**

Oxygenated and non-oxygenated monoterpene emission ( $\text{nmol m}^{-2} \text{s}^{-1}$ ) of rosemary plants at the end of drought and salinity experiments. Results of ANOVA and two-way MANOVA are shown. Asterisks indicate significant differences between well-watered (DC and SC) and drought (DS) or salt stress (SS) plants, differences among various fertilization treatments (C, CA, UP or C, JO, QU) and interactions; n.s.: not significant  $p > 0.05$ ; \*, \*\*: significant at  $p < 0.05$  and  $0.01$ , respectively. For other abbreviations see Tables 1 and 2

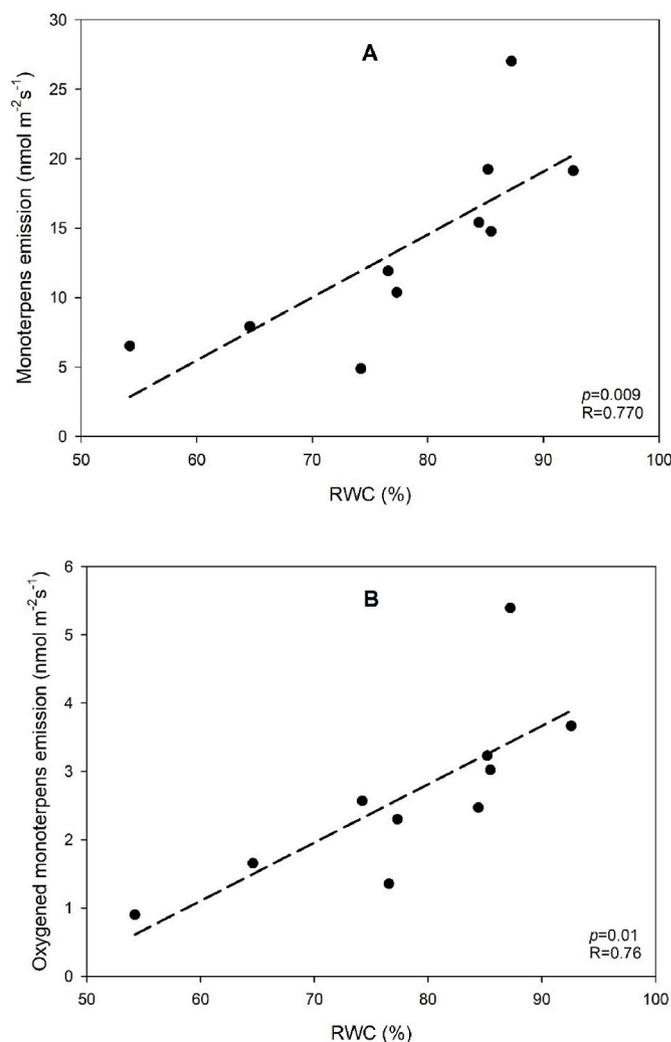
	Non oxygenated monoterpenes ( $\text{nmol m}^{-2} \text{s}^{-1}$ )	Oxygenated monoterpenes ( $\text{nmol m}^{-2} \text{s}^{-1}$ )
<b>Drought experiment</b>		
Compost		
C	12.45	2.28
CA	21.22	4.20
UP	14.37	2.94
Univariate	n.s.	n.s.
(p)	0.565	0.574
Drought treatment		
DC	20.47	3.81
DS	11.35	2.45
Univariate	*	n.s.
(p)	0.041	0.128
Interaction	**	**
Univariate	0.025	0.011
(p)	n.s.	n.s.
<b>Salinity experiment</b>		
Compost		
C	14.75	2.98
JO	14.80	2.52
QU	13.31	2.19
Univariate	n.s.	n.s.
(p)	0.971	0.870
Salt treatment		
SC	16.43	3.05
SS	12.15	2.07
Univariate	n.s.	n.s.
(p)	0.457	0.441
Interaction		
Univariate	n.s.	n.s.
(p)	0.847	0.824

non-oxygenated ( $P = 0.009$ ;  $R = 0.77$ ) monoterpene emissions, excluding data from UP plants (Fig. 4).

A decline in monoterpene emissions during periods of drought has been observed by other researchers. Yani et al. (1993) demonstrated a substantial decline in monoterpene emissions from *Cupressus sempervirens*, a terpen ester-producing species, following an extended drought period. In our previous study, we reported a decrease of non-oxygenated monoterpenes with drought (Nogués et al., 2015). However, oxygenated monoterpenes exhibited an increase, attributed to the cumulative temperature-induced volatilization from storage pools. In fact, the temperatures in that study were higher than those observed in the current study (the temperature ranged from  $23.8^\circ\text{C}$  at the beginning of the experiment to  $33.6^\circ\text{C}$ ). On the other hand, Peñuelas and Llusla (1997) findings, based on a 21-month greenhouse experiment, revealed an absence of a clear correlation between irrigation terpene emissions in rosemary plants. This observation was replicated by Ormeño et al. (2007) in a 11-day drought study.

On the other hand, the monoterpene emission from UP plants under drought stress was not significantly different than that under well water conditions ( $22.29 \pm 5.14$ ,  $12.34 \pm 5.07$ , respectively;  $t$ -test  $P = 0.0754$ ). In these plants, drought combined with high salinity (high EC) likely boosted monoterpene emissions due to increased temperature from stomatal closure, enhanced synthase activity, or use of alternative carbon sources.

Throughout the experimental time monoterpene emissions did not change depending on the compost type or the leaf P and N contents though both elements are necessary for terpene synthesis and there was a significant interaction effect between compost and treatment



**Fig. 4.** Correlation between non-oxygenated monoterpene emission (A) or oxygenated monoterpene emissions (B) and RWC at the end of the experimental time.

(Table 4). N has been demonstrated to promote the electron transport rate and leaf photosynthesis, which in turn provide ATP and carbon substrates available for terpene synthesis (Niinemets et al., 2002; Chrysargyris et al., 2016; Perchlik and Tegeder, 2018). Conversely, terpenoid precursors exhibit high-energy phosphate bonds. Furthermore, phosphorus is a constituent of the ATP and NADPH molecules, which are essential for terpenoid synthesis (Bustamante et al., 2020). Other authors have also reported a lack of correlation between monoterpene emissions and N or P foliar concentrations for different species (Blanch et al., 2007). In contrast, Ormeño et al. (2009) demonstrated a positive correlation between N fertilization and terpene emissions in *Rosmarinus officinalis*, although this relationship was only observed under optimal soil N conditions. Indeed, terpene emissions from plants located in plots with the highest compost rates (leaf N = 1.05 %) were as low as in control plots (leaf N = 0.82 %). In the present study, leaf N levels were found to exceed 1.75 %, thus indicating supra-optimal levels with regards to the observation made by these authors. Regarding leaf P, Ormeño et al. (2009) also found a positive correlation with monoterpene emissions in rosemary plants but only when P levels were below 0.13 %. Over this value they did not observe a relationship between leaf P and monoterpene emissions. In our study leaf P levels were always over 0.14 %.

### 3.5. Reflectance indices

The Normalized Difference Vegetation Index (NDVI) is among the earliest vegetation indexes ever calculated and still wanted for its ability to condensate a broad array of vegetation properties into a simplified information about vegetation stress (Huang et al., 2021). For the same reason, it cannot be considered as a universally effective index especially for structural indexes. In the present study is coupled with Modified Chlorophyll Absorption Ratio Index (MCARI 1). Additionally to structural indexes, chlorophyll (Transformed Chlorophyll Absorption in Reflectance Index - TCARI) and carotenoid (Carotenoid Reflectance Index - CRI, Photochemical Reflectance Index - PRI and Plant Senescence Reflectance Index - PSRI) indexes were also taken into account to provide insights into the pigment composition and, consequently, to photosynthetic activity (Gitelson et al., 2017).

A Two-Way MANOVA was conducted to explore the combined effects of compost and drought stress on the following pigment indexes: NDVI, PRI, PSRI, TCARI, CRI and MCARI1. The multivariate test revealed significant effects for both substrate and Treatment, (Wilk's Lambda = 0.133, F = 1.749, P < 0.045  $\eta^2 = 0.396$ ) and (Wilk's Lambda = 0.085, F = 26.766, P < 0.001  $\eta^2 = 0.915$ ), respectively. The interaction between compost used and Treatment applied was not significant (Wilk's Lambda = 0.220, F = 1.214, P < 0.272  $\eta^2 = 0.315$ ) suggesting a not combined influence of both factors on plant's pigment indexes. Post-hoc contrast was carried out by Tukey HSD (P < 0.05).

Drought stress increased PSRI (P < 0.001) and TCARI (P < 0.001), whereas it decreased NDVI (P < 0.001), PRI (P < 0.001), CRI (P = 0.023), and MCARI1 (P = 0.005) (Table 5). Our findings indicate that all the indices examined demonstrate sensitivity to drought, thereby indicating their potential to serve as effective indicators of drought stress in rosemary plants. Nonetheless, it was observed that PRI and PSRI exhibited a greater response to water stress compared to other hyperspectral parameters. PRI index has been shown to be a reliable metric for measuring the activity of the xanthophyll cycle which is related to photosynthetic light-use efficiency in plants (Coops et al., 2010). On the other hand, the PSRI index was first proposed by Merzlyak et al. (1999) as a sensor of the ratio of carotenoid to chlorophyll content and of the senescence phase of plant development. In a related study, Zhou et al. (2021) reported a change in PRI because of drought in citrus trees. Concurrently, Suárez et al. (2011) reported that PRI can be used as an indicator of water stress in peach orchards. Regarding PSRI index, it has been reported that is a valuable proxy in determining secondary effects of water stress (Struthers et al., 2013).

Regarding composts, plants grown on soils amended with UP compost presented a significantly higher TCARI than control plants. These high TCARI values, overall, under control conditions, could be related to the high CEC values of UP compost. Indeed, it must be considered that, despite elevated N levels, UP plants exhibited a diminished biomass in comparison to alternative treatments. This observation signifies the presence of an additional factor, such as a high EC that hindered plant growth and maybe also other metabolic pathways reflected in this index. In this regard, Medina (2024) elucidates a mechanism of solute synthesis, designated as "compatible solutes", which operates within the cytoplasm of plant cells. This mechanism functions to counteract the osmotic potential of vacuoles, thereby facilitating adaptation to saline environments. The synthesis of these compatible solutes is predicted to incur a higher energetic cost for the plant and a higher nitrogen (N) consumption. This has been hypothesized to explain a shift in metabolic pathways that decreases chlorophyll synthesis in favor of increasing solutes and combating salt stress. On the other hand, the notion that interpretation of this index is challenging in cases of low leaf area (Liao et al., 2014) also must be considered.

A Two-Way MANOVA was conducted to explore the combined effects of compost and salt stress on the following pigment indexes: NDVI, PRI, PSRI, TCARI, CRI and MCARI1. The multivariate test revealed significant effects for both compost and Treatment, (Wilk's Lambda =

**Table 5**

The table shows mean values for NDVI, PRI, PSRI, TCARI, CRI and MCARI1. Asterisks indicate significant differences between well-watered (DC and SC) and drought (DS) or salt stress (SS) plants, differences among various fertilization treatments and interactions. n.s.: not significant p > 0.05; \*, \*\*, \*\*\*: significant at p < 0.05, 0.01 and 0.001, respectively. For each parameter and factor, values in columns followed by the same letter are not statistically significant according to the Tukey HSD test. For other abbreviations see Tables 1, 2 and 4.

	NDVI	PRI	PSRI	TCARI	CRI	MCARI1
<i>Drought experiment</i>						
<i>Compost</i>						
C	0.708	-0.018	0.042	0.147 b	7.330	0.512
CA	0.705	-0.017	0.034	0.184 ab	6.613	0.495
SA	0.679	-0.017	0.045	0.185 ab	6.462	0.468
TO	0.638	-0.026	0.061	0.184 ab	6.539	0.461
UP	0.679	-0.024	0.038	0.236 a	5.129	0.540
<i>Univariate (p)</i>	n.s.	n.s.	n.s.	**	n.s.	n.s.
<i>Drought treatment</i>						
DC	0.792	-0.004	0.009	0.116	8.792	0.574
DS	0.571	-0.037	0.078	0.258	4.037	0.416
<i>Univariate (p)</i>	***	***	***	***	***	***
<i>Interaction Co x T (p)</i>	<0.001	<0.001	<0.001	<0.001	0.023	0.005
<i>Salinity experiment</i>						
<i>Compost</i>						
C	0.728 b	-0.021 b	0.031 a	0.185 a	7.586 b	0.495 b
FO	0.746 b	-0.015 b	0.026 a	0.158 a	8.233 ab	0.494 b
JO	0.760 ab	-0.013 ab	0.022 ab	0.154 a	8.260 ab	0.539 ab
QU	0.727 b	-0.020 b	0.033 a	0.186 a	7.843 b	0.506 ab
TI	0.793 a	-0.003 a	0.012 b	0.095 b	9.329 a	0.569 a
<i>Univariate (p)</i>	***	***	***	***	***	***
<i>Salt treatment</i>						
SC	0.757	-0.011	0.022	0.156	8.043	0.540
SS	0.745	-0.018	0.027	0.156	8.458	0.501
<i>Univariate (p)</i>	n.s.	**	n.s.	n.s.	n.s.	**
<i>Interaction Co x T (p)</i>	0.218	0.014	0.084	0.991	0.15	0.012
<i>Interaction Co x T</i>						
<i>Univariate (p)</i>	0.018	0.037	0.046	0.002	<0.001	0.034
	**	*	*	**	***	*

0.209, F = 3.734, P < 0.001,  $\eta^2 = 0.324$ ) and (Wilk's Lambda = 0.625, F = 4.506, P < 0.001  $\eta^2 = 0.375$ ), respectively. The interaction between compost used and Treatment applied was also significant (Wilk's Lambda = 0.145, F = 4.864, P < 0.001  $\eta^2 = 0.382$ ) suggesting a combined influence of both factors on plant's pigment indexes. Post-hoc contrast was carried out by Tukey HSD (P < 0.05).

Salt stress decreased PRI (p = 0.014) and MCARI1 (p = 0.012). PRI reduction after 28 and 35 days of salt stress were found by Calzone et al. (2021) in two different pomegranate cultivars.

With regards to the effect of compost, TI plants presented higher NDVI, PRI, CRI and MCARI1 values and lower PSRI and TCARI values than control plants (Table 5). These variations were in the opposite direction to those caused by drought stress. Although, specific conclusions cannot be drawn relying exclusively on optical indexes, our findings suggest TI plants cope better with salinity stress in comparison with other plants indicating improvement of structure indexes.

#### 4. Conclusions

From the standpoint of biomass, it was determined that CA compost was the most suitable amendment to be employed under conditions of drought stress. Conversely, UP and TO were found to be suboptimal under drought conditions, although TO compost did promote plant growth under normal irrigation conditions. UP compost presented a high electrical conductivity (EC) value, which may have an impact on plant growth even under full irrigation. Conversely, TO compost has been observed to contain comparatively low levels of humic substances, which are known to facilitate plant resilience in drought-stressed environments.

With regard to salinity, both JO and FO compost appear to be more conducive to plant growth under conditions of salinity. Leaves of plants cultivated on FO-amended soils exhibit elevated levels of the K/Na ratio, which is widely regarded as an indicator of salt tolerance. However, the leaf K/Na ratio of plants treated with JO was the lowest among the treatments. It can thus be concluded that, in the context of salt stress, JO plants have been shown to be capable of compensating for the negative effects that ion imbalances may have on plant growth.

As previously reported by several authors, an increase in monoterpene emission was observed at the onset of drought and salt stress. Furthermore, a positive correlation was identified between leaf relative water content (RWC) and monoterpene emission rates, with the exception of the UP leaves data, at the conclusion of the experimental period. The use of UP compost with elevated EC, impaired plant growth despite the presence of elevated levels of leaf N. This phenomenon also led to the disruption of other processes, including the emission rates of monoterpenes.

With regard to reflectance indices, the impact of drought was observed to exert an influence on all indices that were the subject of study (NDVI, PRI, PSRI, TCARI, CRI and MCARI1). Conversely, salinity was found to have no effect on index values. It is noteworthy that UP leaves exhibited notably elevated TCARI values in comparison to the other treatments, thereby emulating the effect of drought on this index. High EC compost likely caused stress and reduced chlorophyll synthesis in rosemary. Conversely, TI leaves showed strong index changes opposite to drought effects. This result may suggest that TI plants demonstrated superior performance under conditions of control and/or salt stress, though this higher performance had not been reflected in plant growth under salt stress.

#### CRedit authorship contribution statement

**C. Álvarez-Alonso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **I. Nogues:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Pallozzi:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **W. Stefanoni:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **F. Pietrini:** Writing – original draft, Validation, Software, Resources, Methodology, Investigation. **L. Sosa:** Validation, Software, Methodology, Investigation. **N. Manrique-Cordoba:** Methodology, Investigation. **M.D. Perez-Murcia:** Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **R. Moral:** Validation, Resources, Methodology, Investigation. **M.A. Bustamante:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

This research has been financed by the research project NEOCOMP (ref. PID2020-113228RBI00) funded by MCIN/AEI/10.13039/501100011033, and it was supported by the Spanish Ministry of Universities with a PhD contract (FPU21/01207) to the first author. The activities were also funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of December 16, 2021, rectified by Decree n.3175 of December 18, 2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU; Project code CN\_00000033, Concession Decree No. 1034 of June 17, 2022 adopted by the Italian Ministry of University and Research, Project title “National Biodiversity Future Center - NBFC” and by EU - Next Generation EU Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realization of an integrated system of research and innovation infrastructures” - [grant number IR0000032 – ITINERIS - Italian Integrated Environmental Research Infrastructures System - CUP B53C22002150006].

#### Data availability

Data will be made available on request.

#### References

- Acosta-Motos, J.R., Ortuño, M.F., Bernal-Vicente, A., Diaz-Vivancos, P., Sanchez-Blanco, M.J., Hernandez, J.A., 2017. Plant responses to salt stress: adaptive mechanisms. *Agronomy* 7 (1), 18. <https://doi.org/10.3390/agronomy7010018>.
- Alburquerque, J.A., de la Fuente, C., Bernal, M.P., 2011. Improvement of soil quality after “Alperujo” compost application to two contaminated soils characterised by differing heavy metal solubility. *J. Environ. Manage.* 92 (3), 733–741. <https://doi.org/10.1016/J.JENVMAN.2010.10.018>.
- Alsadon, A., Dewir, Y.H., Ibrahim, A., Alenazi, M., Osman, M., Al-Selwey, W.A., Ali, M. A., Shady, M., Alsughayyir, A., Hakiman, M., 2024. Compost amendment enhances leaf gas exchange, growth, and yield in water-challenged ‘Crimson Giant’ red radish (*Raphanus sativus* L.). *Hortscience* 59 (1), 84–91. <https://doi.org/10.21273/HORTSCI17371-23>.
- Álvarez-Alonso, C., Pérez-Murcia, M.D., Manrique, N., Andreu-Rodríguez, F.J., Miras-Urios, M.A., Irigoyen, I., López, M., Orden, L., Moral, R., Nogués, I., Bustamante, M.A., 2025. Agronomic use of urban composts from decentralized composting scenarios: implications for a horticultural crop and soil properties. *Agronomy* 15 (7), 1520.
- Álvarez-Alonso, C., Pérez-Murcia, M.D., Sánchez-Méndez, S., Martínez-Sabater, E., Irigoyen, I., López, M., Nogués, I., Paredes, C., Orden, L., García-Rández, A., Bustamante, M.A., 2024. Municipal solid waste management in a decentralized composting scenario: assessment of the process reproducibility and quality of the obtained composts. *Agronomy* 14 (1), 54. <https://doi.org/10.3390/agronomy14010054>.
- Aly, M., Mohamed, R., Hassan, A., 2024. Alleviation of irrigation water salinity effect on *rosmarinus Officinalis* by humic acid. *Scientific Journal of Agricultural Sciences* 6 (1), 1–16. <https://doi.org/10.21608/sjas.2024.268089.1388>.
- Ashraf, M., Harris, P., 2004. Potential biochemical indicators of salinity tolerance in plants. *Plant Sci.* 166, 3–16. <https://doi.org/10.1016/j.plantsci.2003.10.024>.
- Atiyeh, R.M., Edwards, C.A., Subler, S., Metzger, J.D., 2001. Pig manure vermicompost as a component of a horticultural bedding plant medium: effects on physicochemical properties and plant growth. *Bioresour. Technol.* 78 (1), 11–20. [https://doi.org/10.1016/S0960-8524\(00\)00172-3](https://doi.org/10.1016/S0960-8524(00)00172-3).
- Blanch, J.S., Peñuelas, J., Llusà, J., 2007. Sensitivity of terpene emissions to drought and fertilization in terpene-storing *Pinus halepensis* and non-storing *Quercus ilex*. *Physiol. Plant.* 131 (2), 211–225. <https://doi.org/10.1111/j.1399-3054.2007.00944.x>.
- Bremner, J.M., Britebeck, G.A., 1983. A simple method for determination of ammonium in semimicro-Kjeldahl analysis of soils and plant materials using a block digester. *Commun. Soil Sci. Plan.* 14 (10), 905–913. <https://doi.org/10.1080/00103628309367418>.
- Bremner, J.M., Keeney, D.R., 1965. Steam distillation methods for determination of ammonium, nitrate and nitrite. *Anal. Chim. Acta* 32 (C), 485–495. [https://doi.org/10.1016/S0003-2670\(00\)88973-4](https://doi.org/10.1016/S0003-2670(00)88973-4).
- Brinton, W.F., Evans, E., Droffner, M.L., Brinton, R.B., 1995. A standardized dewar test for evaluation of compost self-heating. *Biocycle* 36, 1–16.

- Bustamante, M.A., Alburquerque, J.A., Restrepo, A.P., de la Fuente, C., Paredes, C., Moral, R., Bernal, M.P., 2012. Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. *Biomass Bioenergy* 43, 26–35. <https://doi.org/10.1016/j.biombioe.2012.04.010>.
- Bustamante, M.Á., Michelozzi, M., Caracciolo, A.B., Grenni, P., Verbokkem, J., Geerdink, P., Safi, C., Nogueis, I., 2020. Effects of soil fertilization on terpenoids and other carbon-based secondary metabolites in *rosmarinus Officinalis* plants: a comparative study. *Plants* 9 (7), 1–19. <https://doi.org/10.3390/plants9070830>.
- Byron, J., Kreuzwieser, J., Purser, G., van Haren, J., Ladd, S.N., Meredith, L.K., Werner, C., Williams, J., 2022. Chiral monoterpenes reveal forest emission mechanisms and drought responses. *Nature* 609 (7926), 307–312. <https://doi.org/10.1038/s41586-022-05020-5>.
- Calzone, A., Cotrozzi, L., Lorenzini, G., Nali, C., Pellegrini, E., 2021. Hyperspectral detection and monitoring of salt stress in pomegranate cultivars. *Agronomy* 11 (6), 1038. <https://doi.org/10.3390/agronomy11061038>.
- Caon, L., Vargas, R., 2017. Threats to soils: global trends and perspectives. Global soil partnership food and agriculture organization of the united nations, brajendra. A Contribution from the Intergovernmental Technical Panel on Soils. Global land outlook working paper.
- Chaves, M.M., Flexas, J., Pinheiro, C., 2009. Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Ann. Bot.* 103 (4), 551–560. <https://doi.org/10.1093/aob/mcn125>.
- Choi, S., Harvey, J.T., Leskovar, D.I., 2024. Solid humic substance enhanced spinach abiotic stress tolerance under combined drought, salinity, and daily heat stress. *Plant Stress* 13, 100544. <https://doi.org/10.1016/j.stress.2024.100544>.
- Coops, N.C., Hilker, T., Hall, F.G., Nichol, C.J., Drolet, G.G., 2010. Estimation of light-use efficiency of terrestrial ecosystems from space: a status report. *Bioscience* 60 (10), 788–797. <https://doi.org/10.1525/bio.2010.60.10.5>.
- Chrysargyris, A., Panayiotou, C., Tzortzakis, N., 2016. Nitrogen and phosphorus levels affected plant growth, essential oil composition and antioxidant status of lavender plant (*Lavandula angustifolia* mill.). *Ind. Crop. Prod.* 83, 577–586. <https://doi.org/10.1016/j.indcrop.2015.12.067>.
- Daba, A.W., 2025. Rehabilitation of soil salinity and sodicity using diverse amendments and plants: a critical review. *Discov. Environ.* 3, 53. <https://doi.org/10.1007/s44274-025-00199-6>.
- DIN EN 12176, 1998. Characterization of Sludge—Determination of pH Value. Deutsches Institut für Normung, Berlin, Germany, 1998.
- Duan, Q., Kleiber, A., Jansen, K., Junker, L.V., Kammerer, B., Han, G., Zimmer, I., Rennenberg, H., Schnitzler, J.P., Ensminger, I., Gessler, A., Kreuzwieser, J.F., 2019. Effects of elevated growth temperature and enhanced atmospheric vapor pressure deficit on needle and root terpenoid contents of two douglas fir provenances. *Environ. Exp. Bot.* 166, 103819. <https://doi.org/10.1016/j.envexpbot.2019.103819>.
- Eekhout, J.P.C., Nunes, J.P., Trambly, Y., de Vente, J., 2025. Severe impacts on water resources projected for the Mediterranean Basin. *Wiley Interdisciplinary Reviews: Water* 12 (2). <https://doi.org/10.1002/wat2.70012>.
- Ferreira, C.S.S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., Kalantari, Z., 2022. Soil degradation in the european mediterranean region: processes, status and consequences. *Sci. Total Environ.* 805, 150106. <https://doi.org/10.1016/j.scitotenv.2021.150106>.
- Filcheva, E.G., Tsadilas, C.D., 2002. Influence of clinoptilolite and compost on soil properties. *Commun. Soil Sci. Plant Anal.* 33 (3–4), 595–607. <https://doi.org/10.1081/CSS-120002766>.
- Formica, V., Leoni, F., Duce, C., González-Rivera, J., Onor, M., Guarnaccia, P., Carlesi, S., Bärberi, P., 2024. Controlled drought stress affects rosemary essential oil composition with minimal impact on biomass yield. *Ind. Crops Prod.* 221, 119315. <https://doi.org/10.1016/j.indcrop.2024.119315>.
- Gajalakshmi, S., Abbasi, S.A., 2008. Solid waste management by composting: state of the art. *Crit. Rev. Env. Sci. Technol.* 38 (5), 311–400. <https://doi.org/10.1080/10643380701413633>.
- García-López, A.M., Horta, C., 2022. Effects of compost on lettuce (*Lactuca sativa*) yield and soil biochemical properties. *Rev. Ciencias Agrar.* 45, 421–430. <https://doi.org/10.19084/rca.28488>.
- Geisseler, D., Miller, K., Santiago, S., Abou Najm, M., 2024. The multi-faceted relationship between nitrogen mineralization and soil texture. *Soil Sci. Soc. Am. J.* 88 (5), 1792–1807. <https://doi.org/10.1002/saj2.20728>.
- Gitelson, A.A., Gamon, J.A., Solovchenko, A., 2017. Multiple drivers of seasonal change in PRI: implications for photosynthesis 1. Leaf level. *Remote Sens. Environ.* 191, 110–116. <https://doi.org/10.1016/j.rse.2016.12.014>.
- Hernández, T., Chocano, C., Moreno, J.L., García, C., 2016. Use of compost as an alternative to conventional inorganic fertilizers in intensive lettuce (*Lactuca sativa* L.) crops-effects on soil and plant. *Soil Tillage Res.* 160, 14–22. <https://doi.org/10.1016/j.still.2016.02.005>.
- Huang, S., Tang, L., Hupy, J.P., Wang, Y., Shao, G., 2021. A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *J. For. Res.* 32 (1), 1–6. <https://doi.org/10.1007/s11676-020-01155-1>.
- Jamaladdeen, R., Coudour, B., Dédaldéchamp, F., Lemée, L., Thibault, F., Garo, J.P., Wang, H.Y., 2023. Influence of combined hydric and thermal stresses on *rosmarinus officinalis* and *Cistus albidus*. *Int. J. Wildland Fire* 32 (6), 968–978. <https://doi.org/10.1071/WF22146>.
- Kamanga, R.M., Matuntha, I., Chawanda, G., Mtaya, J., Chasweka, T., Dzimbiri, C., Stevens, J., Nyasulu, M., Chiyawa, H., Sefasi, A., Mwale, V.M., Chimungu, J., 2024. Exploration of agronomic efficacy and drought amelioration ability of municipal solid waste-derived Co-Compost on lettuce and maize. *Sustainability* 16 (23), 10548. <https://doi.org/10.3390/su162310548>.
- Karlen, D.L., Rice, C.W., 2015. Soil degradation: will humankind ever learn? *Sustainability* 7, 12490–12501. <https://doi.org/10.3390/su70912490>.
- Khorasani, H., Rajabzadeh, F., Mozafari, H., Pirbalouti, A.G., 2023. Water deficit stress impairment of morphophysiological and phytochemical traits of stevia (*Stevia rebaudiana* bertonii) buffered by humic acid application. *S. Afr. J. Bot.* 154, 365–371. <https://doi.org/10.1016/j.sajb.2023.01.030>.
- Li, P., Huang, X., Yin, S., Bao, Y., Bao, G., Tong, S., et al., 2023. Optimizing spectral index to estimate the relative chlorophyll content of the forest under the damage of *Erannis jacobsoni* djak in Mongolia. *Ecol. Indic.* 154, 110714. <https://doi.org/10.1016/j.ecolind.2023.110714>.
- Liao, Q.H., Zhang, D.Y., Wang, J.H., Yang, G.J., Yang, H., Craig, C., Wong, Z., Wang, D. C., 2014. Assessment of chlorophyll content using a new vegetation index based on multi-angular hyperspectral image data. *Spectrosc. Spectr. Anal.* 34 (6), 1599–1604. [https://doi.org/10.3964/j.issn.1000-0593\(2014\)06-1599-06](https://doi.org/10.3964/j.issn.1000-0593(2014)06-1599-06).
- Medina, E., 2024. Principios de ecofisiología vegetal. Ediciones IVIC. Instituto Venezolano De Investigaciones Científicas, p. 414. Caracas, Venezuela.
- Melero, S., Madejón, E., Ruiz, J.C., Herencia, J.F., 2007. Chemical and biochemical properties of a clay soil under dryland agriculture system as affected by organic fertilization. *Eur. J. Agron.* 26 (3), 327–334. <https://doi.org/10.1016/j.eja.2006.11.004>.
- Merzlyak, M.N., Gitelson, A.A., Chivkunova, O.B., Rakin, V.Y., 1999. Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiol. Plant.* 106 (1), 135–141. <https://doi.org/10.1034/j.1399-3054.1999.106119.x>.
- Mira-Urios, M.Á., Sáez, J.A., Orden, L., Marhuenda-Egea, F.C., Andreu-Rodríguez, F.J., Toribio, A.J., Agulló, E., López, M.J., Moral, R., 2025. Composting of olive mill wastewater sludge using a combination of multiple strategies: assessment of improvement in biodegradability, GHG emissions, and characteristics of the end product. *Agronomy* 15 (4), 808. <https://doi.org/10.3390/agronomy15040808>.
- Munné-Bosch, S., Alegre, L., 2000. Changes in carotenoids, tocopherols and diterpenes during drought and recovery, and the biological significance of chlorophyll loss in *rosmarinus Officinalis* plants. *Planta* 210, 925–931. <https://doi.org/10.1007/s004250050699>.
- Munns, R., 2002. Comparative physiology of salt and water stress. *Plant Cell Environ.* 25 (2), 239–250. <https://doi.org/10.1046/j.0016-8025.2001.00808.x>.
- Nestola, E., Scartazza, A., Di Baccio, D., Castagna, A., Ranieri, A., Cammarano, M., Mazzenga, F., Matteucci, G., Calfapietra, C., 2018. Are optical indices good proxies of seasonal changes in carbon fluxes and stress-related physiological status in a beech forest? *Sci. Total Environ.* 612, 1030–1041. <https://doi.org/10.1016/j.scitotenv.2017.08.167>.
- Niinemetts, U., Hauff, K., Bertin, N., Tenhunen, J.D., Steinbrecher, R., Seufert, G., 2002. Monoterpene emissions in relation to foliar photosynthesis and structural variables in mediterranean evergreen *quercus* species. *New Phytol.* 153, 243–256. <https://doi.org/10.1046/j.0028-646X.2001.00323.x>.
- Nogués, I., Muzzini, V., Loreto, F., Bustamante, M.A., 2015. Drought and soil amendment effects on monoterpene emission in rosemary plants. *Sci. Total Environ.* 538, 768–778. <https://doi.org/10.1016/j.scitotenv.2015.08.080>.
- Ormeño, E., Olivier, R., Mévy, J.P., Baldy, V., Fernandez, C., 2009. Compost May affect volatile and semi-volatile plant emissions through nitrogen supply and chlorophyll fluorescence. *Chemosphere* 77 (1), 94–104. <https://doi.org/10.1016/j.chemosphere.2009.05.014>.
- Ormeño, E., Mévy, J.P., Vila, B., Bousquet-Mélou, A., Greff, S., Bonin, G., Fernandez, C., 2007. Water deficit stress induces different monoterpene and sesquiterpene emission changes in Mediterranean species. Relationship between terpene emissions and plant water potential. *Chemosphere* 67 (2), 276–284. <https://doi.org/10.1016/j.chemosphere.2006.10.029>.
- Peñuelas, J., Llusla, J., 1997. Effects of carbon dioxide, water supply, and seasonality on terpene content and emission by *rosmarinus officinalis*. *J. Chem. Ecol.* 23 (4), 979–993. <https://doi.org/10.1023/B:JOEC.000006383.29650.d7>.
- Pietrini, F., Passatore, L., Carloni, S., Massimi, L., Astolfi, M.L., Giusto, C., Zacchini, M., 2023. Bismuth exposure affects morpho-physiological performances and the ionic profile in garden cress (*Lepidium sativum* L.) plants. *Front. Environ. Sci.* 11, 1221573.
- Perchlik, M., Tegeder, M., 2018. Leaf amino acid supply affects photosynthetic and plant nitrogen use efficiency under nitrogen stress. *Plant Physiol* 178 (1), 174–188. <https://doi.org/10.1104/pp.18.00597>.
- Radwan, A., Kleinwächter, M., Selmar, D., 2017. Impact of drought stress on specialised metabolism: biosynthesis and the expression of monoterpene synthases in sage (*Salvia officinalis*). *Phytochemistry* 141, 20–26. <https://doi.org/10.1016/j.phytochem.2017.05.005>.
- Rahman, S.U., Yousaf, S., Ilyas, M., Su, Y., Riaz, M., Ditta, A., Ayub, G., 2023. Comparative study of differently composted organic fraction of municipal solid waste: insights from physicochemical analysis. *Research Square*. <https://doi.org/10.21203/rs.3.rs-3065595/v1>.
- Rodrigues, M.S., Dias, L.F., Nunes, J.P., 2024. Impact of nature-based solutions on sustainable development goals in Mediterranean agroecosystems: a meta-analysis. *J. Environ. Manage.* 371, 123071. <https://doi.org/10.1016/j.jenvman.2024.123071>.
- Salem, O.H., Jia, Z., 2024. Evaluation of different soil salinity indices using remote sensing techniques in Siwa oasis, Egypt. *Agronomy* 14 (4), 723. <https://doi.org/10.3390/agronomy14040723>.
- Savy, D., Cozzolino, V., Vinci, G., Verrillo, M., Aliberti, A., Maggio, A., Barone, A., Piccolo, A., 2022. Fertilisation with compost mitigates salt stress in tomato by affecting plant metabolomics and nutritional profiles. *Chem. Biol. Technol. Agric.* 9, 104. <https://doi.org/10.1186/s40538-022-00373-5>.
- Schurgers, G., Arneth, A., Holzinger, R., Goldstein, A.H., 2009. Process-based modelling of biogenic monoterpene emissions combining production and release from storage. *Atmos. Chem. Phys.* 9. <https://doi.org/10.5194/acp-9-3409-2009>.

- Struthers, R.R., Farifteh, J., Swennen, R., Coppin, P., 2013. Physiological and spectral response to water stress induced by regulated deficit irrigation on pear trees. *Appl. Rem. Sens. J.* 3, 9–17.
- Suárez, L., Zarco-Tejada, P.J., Berni, J.A.J., González-Dugo, V., Fereres, E., 2011. Orchard water stress detection using high-resolution imagery. *Acta Hort.* 922, 35–39. <https://doi.org/10.17660/ActaHortic.2011.922.3>.
- Suwendran, S., Acevedo, M.F., Smithers, B., Walker, S.J., Xu, P., 2025. Soil fertility and plant growth enhancement through compost treatments under varied irrigation conditions. *Agriculture* 15 (7). <https://doi.org/10.3390/agriculture15070734>.
- Tomescu, D., Şumălan, R., Copolovici, L., Copolovici, D., 2017. The influence of soil salinity on volatile organic compounds emission and photosynthetic parameters of *Solanum lycopersicum* L. varieties. *Open Life Sci.* 12 (1), 135–142. <https://doi.org/10.1515/biol-2017-0016>.
- Tounekti, T., Vadel, A.M., Bedoui, A., Khemira, H., 2008. NaCl stress affects growth and essential oil composition in rosemary (*Rosmarinus officinalis* L.). *J. Hort. Sci. Biotechnol.* 83 (2), 267–273. <https://doi.org/10.1080/14620316.2008.11512379>.
- Tounekti, T., Vadel, A.M., Oñate, M., Khemira, H., Munné-Bosch, S., 2011. Salt-induced oxidative stress in rosemary plants: damage or protection? *Environ. Exp. Bot.* 71 (2), 298–305. <https://doi.org/10.1016/j.envexpbot.2010.12.016>.
- Turbé, A., De Toni, A., Benito, P., Lavelle, P., Ruiz, N., Van der Putten, W.H., Labouze, E., Mudgal, S., 2010. Soil biodiversity: functions, threats and tools for policy makers. Bio Intelligence service, IRD and NIOO, report for european commission (DG environment). <https://hal-bioemco.ccsd.cnrs.fr/bioemco-00560420v1>.
- Valifard, M., Mohsenzadeh, S., Kholdebarin, B., Rowshan, V., Niazi, A., Moghadam, A., 2018. Effect of salt stress on terpenoid biosynthesis in *salvia Mirzayanii*: from gene to metabolite. *J. Hort. Sci. Biotechnol.* 94 (3), 389–399. <https://doi.org/10.1080/14620316.2018.1505443>.
- Valverde-Orozco, V., Gavilanes-Terán, I., Idrovo-Novillo, J., Ramos-Romero, S., Valverde-Quiroz, D., Idrovo-Gavilanes, J., Paredes, C., 2024. Approach to the circular economy through agro-livestock waste composting with heat recovery and agricultural use of the resulting compost. *Sustainable Chem. Pharm.* 41, 101730. <https://doi.org/10.1016/j.scp.2024.101730>.
- Wang, W., Zhang, D., Kong, H., Zhang, G., Shen, F., Huang, Z., 2024. Effects of salinity accumulation on physical, chemical, and microbial properties of soil under rural domestic sewage irrigation. *Agronomy* 14, 514. <https://doi.org/10.3390/agronomy14030514>.
- Yani, A., Pauly, G., Faye, M., Salin, F., Gleizes, M., 1993. The effect of a long-term water stress on the metabolism and emission of terpenes of the foliage of *Cupressus sempervirens*. *Plant Cell Environ.* 16, 975–981. <https://doi.org/10.1111/j.1365-3040.1993.tb00521.x>.
- Yeomans, J.C., Bremner, J.M., 1988. A rapid and precise method for routine determination of organic carbon in soil. *Commun. Soil Sci. Plant Anal.* 19 (13), 1467–1476. <https://doi.org/10.1080/00103628809368027>.
- Zapata-González, D.A., Trujillo-González, J.M., Torres-Mora, M.A., González-Santamaria, D., Jiménez-Ballesta, R., 2023. Assessment of toxic response of *lactuca sativata* compost extracted from agri-food waste. *Int. J. Recycl. Org. Waste Agric.* 13 (1), 132404–132405. <https://doi.org/10.57647/j.ijrowa.2024.1301.04>.
- Zhou, J.J., Zhang, Y.H., Han, Z.M., Liu, X.Y., Jian, Y.F., Hu, C.G., Dian, Y.Y., 2021. Evaluating the performance of hyperspectral leaf reflectance to detect water stress and estimation of photosynthetic capacities. *Remote Sens.* 13 (11), 2160. <https://doi.org/10.3390/rs13112160>.
- Zucconi, F., Pera, A., Forte, M., de Bertoldi, M., 1981. Evaluating toxicity of immature compost. *Biocycle* 22, 54–57.