

Research Paper

Impact of salinity and harvest date on the yield, phenolic and volatile contents of thyme (*Thymus vulgaris* L.), coriander (*Coriandrum sativum* L.) and dill (*Anethum graveolens* L.)

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ABSTRACT

Salinity is a major abiotic stress factor affecting global agriculture and herb cultivation. Recently, controlled salinity stress has gained attention for enhancing herb quality without decreasing yield quantity. Exposure to 100 mM NaCl significantly decreased yield, SPAD values, and chlorophyll a content. Phenolic acids were the dominant phenolic group, though their levels decreased under salinity. Notably, certain compounds, such as salvianolic acid derivatives and apigenin hexosides (25 % to 75 %), increased. Volatile profiles also shifted, with reductions in monoterpenes and aldehydes and increases in esters (37.2 %) and compounds like carvacrol (78.7 %) in thyme grown under saline conditions. Activities of phenylalanine ammonia-lyase (PAL) and peroxidase (POX) varied significantly among treatments. These results suggest that salinity induces species- and compound-specific responses, offering potential to manipulate stress conditions for improved phytochemical profiles. Further research is needed to optimize controlled stress applications in herb production for enhanced quality and functional value.

1. Introduction

Herbs have long been considered an important and valued commodity, as people have been gathering and using knowledge about them for at least 60,000 years (Narayana et al., 2024). The global medicinal plant and herb industry is currently experiencing significant growth, primarily driven by an escalating demand from consumers, largely attributable to the numerous health benefits attributed to herbal products (Bareetseng, 2022). In Europe, the cultivation of herbs is a pervasive practice, with a dedicated area of >200,000 hectares allocated for the purpose. The most extensive cultivation areas are located in France (52,000 ha), Poland (30,000 ha), and Spain (27,800 ha) (Macaluso, Licciardo, and Carbone, 2024). The demand for specific herbs varies across different regions of Europe, depending on traditions and dietary habits. Furthermore, seasonal fluctuations have been demonstrated to exert an influence on the demand for specific herbs. The most commonly consumed herbs in Europe are parsley, basil, chives, dill and thyme (Hallmann and Sabala, 2020). Furthermore, there is growing interest in non-traditional herbs, such as coriander, primarily due to the influence of Eastern cuisine and consumers' desire for culinary exploration (Krsnik and Erjavec, 2024). Herbs can be grown intensively in soilless systems

(hydroponics), the production of which is constantly rising due to easier control over growing conditions (Čavar Zeljković, Aucique-Perez, Štefelová, and De Diego, 2022). Hydroponic systems can increase the yield of herbs and spices without compromising the quality of the volatile profile or other metabolites (Shanila, S., Nair, Stephen, and Gopinath, 2024).

Thyme (*Thymus vulgaris* L.) is a perennial subshrub that is native to the Mediterranean region and belongs to the Lamiaceae family of flowering plants. The plant exhibits a growth pattern ranging from 10 cm to 35 cm in height, characterized by partially woody stems that bear small, narrow leaves with downward-curved edges and densely hairy undersides (Seyedi, Nafchi, and Reezi, 2024). The spectrum of floral coloration exhibits a gradation from light to dark pink, with the flowers forming dense, cylindrical inflorescences that bloom from June until autumn. The aroma of the leaves and flowers is notably strong and distinctive (Bistgani et al., 2019).

Coriander (*Coriandrum sativum* L.) is an annual plant that belongs to the Apiaceae family. The origins of coriander lie in Asia and North Africa, where it is believed to have been one of the earliest spices. This assertion is supported by the discovery of coriander seeds and dried leaves in pharaohs' tombs, suggesting a long-standing use of this spice in

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ancient times. The plant under consideration grows to a maximum height of 50 cm. Its leaves vary in size, being broad-lobed at the base of the plant and smaller, feathery in appearance higher up on the stem. The leaves are distinguished by a distinctive aroma and a resemblance to parsley. The flowers are diminutive and asymmetrical, with a white or pale pink hue, while the fruit assumes a spherical form, measuring between 3 mm and 5 mm in diameter (Gantait, Sharangi, Mahanta, and Meena, 2022; Hussain *et al.*, 2024).

Dill (*Anethum graveolens* L.) is an annual plant originally from Asia and belongs to the Apiaceae family. The plant is characterized by the presence of hollow stems that are slightly ribbed, and are greyish-green in color. The leaves are repeatedly pinnate in shape and possess a distinctive aroma. The flowers are yellow and bloom in mid-summer in open umbel-like inflorescences, where small, flattened, oval seeds later mature (Shyu, Lin, Chang, Chiang, and Yang, 2009).

All three herbs – dill, coriander, and thyme – possess distinct aromas, which are highly valued in the culinary world. As reported by Foss, Przybyłowicz, and Sawicki (2022), herbs possess a rich profile of volatile and phenolic compounds, which vary among species and cultivars. These bioactive compounds are responsible for the unique fragrances and flavors of herbs, as well as their potential health benefits, including antioxidant and antimicrobial properties. The composition and content of these compounds are influenced by various environmental factors, including soil composition, climate conditions, and agricultural practices.

A significant factor affecting the synthesis and content of volatile and phenolic compounds is abiotic stress, such as salinity, which poses a major challenge in modern agriculture. It has been demonstrated that elevated levels of salinity have the capacity to compromise plant growth and metabolism, thereby inducing osmotic stress and nutrient imbalances (Atta *et al.*, 2023b). However, it is well documented that herbs exhibit a high degree of resilience and adaptability to challenging environmental conditions. As Parida and Das (2005) observed, herbs have a greater capacity to withstand elevated levels of salinity in comparison to other plant species. This attribute renders them a valuable crop in regions affected by soil salinization. It has been hypothesized that moderate salinity stress may result in an augmentation of the synthesis of secondary metabolites, thereby potentially enhancing the aromatic and medicinal properties of herbs (Kaur *et al.*, 2024). The present study seeks to explore the impact of salinity on the composition of herbs, and to what extent controlled stress conditions may enhance the production of certain beneficial compounds (Lungoci *et al.*, 2022).

The objective of the present study is to address this issue by means of a comprehensive and innovative approach, with a view to investigating the impact of salinity on the quality and quantity of hydroponically cultivated dill, coriander, and thyme. This issue has hitherto been the subject of only a limited number of studies. The findings of this study have the potential to enhance our understanding of the methods by which to modify the quality and quantity of herb yield whilst concurrently inducing controlled stress. This enhanced knowledge may be of significant value to the pharmaceutical and agricultural industries, and moreover to human health, as herbs may constitute beneficial food sources.

2. Materials and methods

2.1. Experimental design

An experiment using hydroponics was carried out in Ljubljana (46° 3' 4" N; 14° 30' 18" E) at the Biotechnical Faculty from 20 May to 10 August 2024. Three herb species (thyme (*Thymus vulgaris* L.), coriander (*Coriandrum sativum* L.) and dill (*Anethum graveolens* L.)) were planted in perlite and placed in six 60 L systems. Each system had four plastic pots (20 cm x 20 cm x 30 cm) standing on a plastic plate. The pots were connected to a drip to supply water and minerals. The water and fertilizers were changed every two to three weeks. The mineral solution

was based on research by Kacjan Maršić *et al.* (2021). The pH and electrical conductivity (EC) of the water solution were on average 6.1 and 2.2 dS m⁻¹ for the control treatments and 6.0 and 12.1 dS m⁻¹ for the saline condition, respectively.

We created two different treatments for each type of plant: 1) control (C) and 2) 100 mM NaCl (NaCl). The NaCl (from Sigma Aldrich, MESTO; DRZAVA) is needed after setting up the hydroponic system. We measured pH and electrical conductivity (EC) every week using an electronic meter (CyberScan PCD650; Eutech Instruments, Singapore). When the pH was not in the right range, 74 % H₂SO₄ was added. The greenhouse conditions were an average temperature of 24.1 °C and 70.4 % humidity.

2.2. Herbs sampling for metabolomic analysis and yield determination

The herbs were sampled on three occasions (1st, 2nd and 3rd harvest dates approximately every 10 days) using scissors, in order to replicate the common practice of harvesting herbs. The subjects were weighed using an electronic balance, and subsequently frozen using liquid nitrogen. Following this, they were pulverized into a fine powder using a mill and stored at -80 °C, for the purpose of further study.

2.3. Pigment contents and relative chlorophyll contents in herbs

Relative chlorophyll contents (SPAD) in herbs was determined using a Minolta SPAD-502 chlorophyll meter, Japan. For each treatment and herb species 20 measurements were carried out at each harvest date.

The chlorophyll and carotenoid content was determined based on Wellburn (1994). Three discs (4 mm in diameter) were cut from leaf samples with a punch and placed into Eppendorf tubes containing 500 µl of dimethyl sulfoxide (DMSO) along with a few crystals of magnesium hydroxide carbonate to prevent pigment degradation. The discs were macerated, followed by the addition of another 500 µl of DMSO. For the blank sample the procedure was the same as for the samples, except no discs were added. The samples were incubated in open tubes at 65 °C for two hours, then cooled to room temperature in the dark to prevent light-induced degradation. After incubation, the extracts were transferred to spectrophotometer cuvettes, and absorbance was measured at 480 nm (carotenoids), 649 nm (chlorophyll *b*), and 665 nm (chlorophyll *a*). The pigment concentrations were calculated using Wellburn's equations as reported by Wellburn (1994).

2.4. Extraction, identification, and quantification of phenolic compounds in herbs

The extraction of phenolic compounds was carried out based on Zamljen *et al.* (2023), with minor modifications. Fresh thyme, dill and coriander leaves and stems were ground to a fine dust using liquid nitrogen and a mortar. 0.2 g of fresh herb sample were extracted with 4 ml of 80 % methanol, 3 % formic acid in bi-distilled water. The samples were then placed into an ultrasonic bath for 1 h (0 °C), after sonification centrifuged at 8000 g for 7 min and filtered through a 0.25 µm polyamide filter (Chromafil AO -20/25, Macherey-Nagel, Dueren, Germany). The samples were then stored in 1.5 ml vials at -20 °C.

The individual phenolic substances were identified using tandem mass spectrometry (MS /MS; LTQ XL; Thermo Scientific, Waltham, MA, USA) in negative ion mode. The quantification was carried out on a UHPLC system (Vanquish; Thermo Scientific, Waltham, MA, USA). Further HPLC/MS parameters were previously described by Zamljen *et al.* (2023).

For the calculation of the individual phenolics content their respective standards were used. Where the standards were not available, phenolics were expressed as equivalents of a similar compound. All syringic acid derivatives were calculated based on gallic acid. Sagerinic acid, rosmarinic acid and salvianolic acid derivatives were calculated based on caffeic acid. Eriodyctiol-O-hexosides were calculated based on

epicatechin. Isorhamnetin-3-O-glucuronide was calculated based on isorhamnetin-3-O-rutinoside. Dimethoxycinnamoyl hexoside was calculated based on cinnamic acid. Apigenin hexoside 1 and 2 were calculated based on apigenin-7-glucoside. The individual phenolics content is presented as mg/kg FW.

2.5. Extraction, identification, and quantification of volatile compounds in herbs

The identification and quantification of volatile organic compounds was performed using gas chromatography-mass spectrometry (SPME-GC-MS) following the method described by Zamljen, Zupanc, Grohar, Lojen, and Slatnar (2024) with some modifications. For each repetition, 1 g of sample powder was placed in a 20 ml glass vial, adding 10 µL of internal standard (IS: 3-Nonanone, 2.7 mg/mL in acetonitrile). After sealing with a screw cap/PTFE-silicon septum, the vials were placed in a Shimadzu AOC-20 s autosampler. The sample was incubated at 50 °C for 5 min while agitated at 250 rpm. The conditioning of the DVB/carbon WR/PDMS SPME fiber was performed at 60 °C for 5 min, then inserted into the vial headspace for 40 min at constant shaking at 250 rpm to extract volatiles. The desorption in the injector was performed for 3 min at 250 °C and a split ratio of 1:50.

The individual compounds were separated by a Shimadzu GC-MS QP2020 system equipped with a single quadrupole MS detector and a ZB-wax PLUS capillary column (30 m × 0.25 mm, 0.5 µm film thickness). The carrier gas was helium at a flow rate of 1 mL/min. The temperature gradient program began at 40 °C for 3 min, then increased to 150 °C at 4 °C/min, to 220 °C at 10 °C/min, where it remained for 10 min. The interface and ion source temperatures were maintained at 240 °C, with the mass spectrometer operating at 70 eV ionization energy, a mass scan range of 50–500 m/z, and a scan rate of 2.0 scans per second. VOCs were identified based on their retention times (RTs) and comparisons with commercial spectral libraries (NIST 11 and FFNSC 4). The quantification was performed by considering each peak and internal standard areas, together with external standards (Suppl. Table 4, Suppl. Table 5 and Suppl. Table 6) and samples weight.

2.6. Phenylalanine ammonia lyase assay

The enzyme assay for phenylalanine ammonia lyase (PAL) (EC 4.3.1.24) was carried out as reported by Zamljen, Medic, Hudina, Veberic, and Slatnar (2022), with minor modifications. A quantity of 0.5 g of fresh fruit tissue was mixed with 3 mL of 0.1 M boric acid extraction buffer, which also contained 0.4 % sodium ascorbate, to yield a pH of 8.5. The mixture was then subjected to a centrifugation process at 12,000 × g for a duration of 30 min (5810 R; Eppendorf). The gel chromatography columns (Sephadex G25 medium; Sigma-Aldrich, St. Louis, MI, USA) were conditioned with five successive washes with 1 mL of extraction buffer. In order to remove low molecular weight compounds, the sample supernatants (500 µL) were added to the gel chromatography columns, which were then washed with 400 µL of extraction buffer, and further used as crude extract.

The reaction mixture contained 110 µL of extraction buffer, 80 µL of crude extract, and 10 µL of 10 mM l-phenylalanine. The blank sample contained 190 µL of extraction buffer and 10 µL of 10 mM l-phenylalanine. Following the incorporation of l-phenylalanine, the samples were subjected to a vortex mixer (Top-Mix 94,500; Bioblock Scientific, France, Strasbourg) and subsequently incubated in a preheated oven at 37 °C for 1.5 h. Thereafter, the reaction was terminated by the addition of 20 µL formic acid and 400 µL MeOH. Further identification of trans-cinnamic acid was carried out tandem mass spectrometry (LTQ XL 125; Thermo Scientific, Waltham, MA, USA) as reported by Zamljen *et al.* (2022). The data were presented as units per mg of protein (U/mg protein).

2.7. Peroxidase assay

The POX (EC 1.11.1.7) activity assay was performed as reported by Simkova *et al.* (2023a) on a Genesys 10 S UV-Vis Spectrometer (Thermo-Scientific, USA). The enzyme activity is expressed in units per milligram of protein (U/mg protein). The protein content was analyzed following the Bradford method with minor modifications, according to Simkova *et al.* (2023b).

2.8. Statistical analysis

Statistical analyses were conducted using the R statistical environment [30]. Data are presented as means ± standard error (SE). Differences between treatments were assessed using one-way analysis of variance (ANOVA), followed by Dunnett's test for the comparison among C and NaCl treatment. Statistical significance was determined at a 95 % confidence level ($p < 0.05$).

3. Results

3.1. Yield of hydroponically grown herbs

The yield of thyme, dill and coriander is shown in Fig. 1A. The total yield per plant significantly decreased in all three herbs in 100 mM NaCl treatment compared to the C treatment, with thyme decrease being 74.5 %, dill 50.6 % and coriander 56.8 %, respectively. In thyme, the 1st harvest date showed no differences in yield among C and NaCl treatment. At the 2nd date, the yield of thyme was 68.7 % lower and at the 3rd 94.9 % lower at the NaCl treatment compared to the control. The yield of NaCl grown dill at 1st date was lower for 49.2 %, 2nd date 63.4 % and at the 3rd date 45.5 % compared to the control treatment. The yield of NaCl grown coriander at 1st date was lower for 33.4 %, 2nd date 58.4 % and at the 3rd date 96.8 % compared to the control treatment.

The percentage of dry weight is presented in Fig. 1B. The harvest dates significantly differ between each other for every treatment in all three species. In thyme, the % of dry weight increased in saline conditions compared to the control. In dill, no differences were observed among control and saline-grown plants. In coriander, the saline conditions decreased the percentage of dry weight at the last harvest date by 11 %.

3.2. Photosynthetic pigments of herbs

SPAD value and individual pigment contents are presented in Fig. 2 (A, B). SPAD value in thyme, dill and coriander showed a significant decrease in the NaCl treatment compared to the control at the 2nd and 3rd harvest. A similar occurrence was also observed in dill and coriander 2nd and 3rd harvest. SPAD value of the selected herbs was not influenced by harvest date at the C treatments but was significantly influenced at the NaCl treatments. In terms of individual pigments, chlorophyll a was the most abundant, followed by chlorophyll b and carotenoids. In general (except at thyme C treatment), a strong decreasing trend was observed with harvest date in all treatments. Individual pigment contents in all herbs decreased especially at the 3rd harvest date in NaCl treatments. At the 3rd harvest date the decrease in NaCl treatment compared to the C treatment was in thyme 37.8 %, in dill 64.7 % and in coriander 44.1 %. In all herbs, the pigment that was influenced by NaCl the most was chlorophyll a, with a decrease of 63.1 % (thyme), 39.5 % (dill) and 63.3 % (coriander) respectively, compared to the C treatment.

3.3. Phenolic compounds in salt grown herbs

3.3.1. Identification of phenolic compounds using LC-MS

In thyme, 15 individual phenolic compounds were identified (Table 1): two hydroxybenzoic acid derivatives, seven hydroxycinnamic

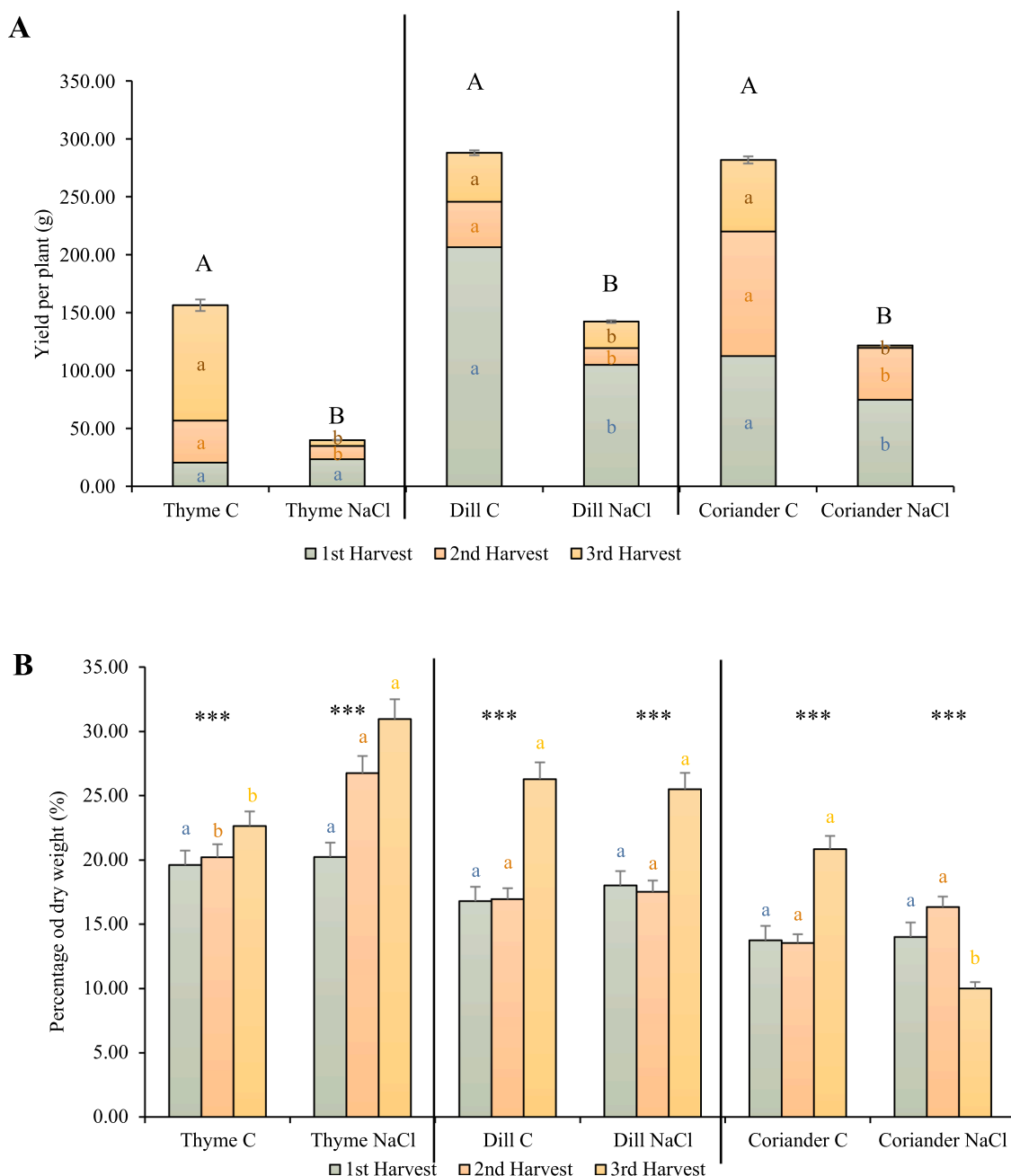


Fig. 1. Herb yield per plant (g) (A) and percentage of dry weight (%) (B) under control (C) and saline (NaCl) conditions for three harvest times (1st, 2nd and 3rd). Lowercase letters (a-b) denote statistical differences for each herb species of herb under the same harvest date. Upper case letters (A-B) denote statistical differences among total yield values for each herb species. *** denotes statistical significant differences among the three harvest dates within the same treatment.

acids derivatives, two flavonols, two flavones and two flavanones. The two hydroxybenzoic acids were syringic acid hexoside 1 and syringic acid hexoside 2, with the typical fragmentation pattern of $MS^1 m/z$ 359 and 197, as reported by [Ahmadi, Fatahi, Zamani, Pocza, and Shokrpour \(2024\)](#). Among the seven identified hydroxycinnamic acids, five of them were salvianolic acid derivatives, with a typical fragmentation pattern of $MS^1 m/z$ 493 and 359, as reported by [Babotă et al. \(2023\)](#). Rosmarinic and sagerinic acids were identified by the typical fragmentation pattern of $MS^1 m/z$ 359, 161 and 179 and $MS^1 m/z$ 557, 359 and 161 respectively, as reported by [Babotă et al. \(2023\)](#). The two flavonols identified in thyme were quercetin-3-O-rutinoside and kaempferol-3-O-hexoside, with a fragmentation pattern of $MS m/z$ 465, MS^2 303 and $MS m/z$ 447, MS^2 285, respectively as reported by [Čulina et al. \(2021\)](#). The two flavones were luteolin-3-O-hexuronide and apigenin-6,8-di-O-glucoside,

with a fragmentation pattern of $MS m/z$ 461, MS^2 285 and $MS m/z$ 593, MS^2 473, 503, respectively as reported by [Ahmadi et al. \(2024\)](#). The two flavanones were identified as eriodictyol-O-hexoside 1 and eriodictyol-O-hexoside 2, with a fragmentation pattern of $MS m/z$ 449, MS^2 287, as reported by [Babotă et al. \(2023\)](#).

In dill, 11 individual phenolics were identified: seven represented hydroxycinnamic acid derivatives, and four flavonols ([Table 2](#)). Chlorogenic and neochlorogenic acids, as well as their derivatives, were identified based on the typical fragmentation pattern of $MS^1 m/z$ 191, 179, 173 and 191, 179, 135, respectively, as reported by [Abdallah et al. \(2024\)](#). The four flavonols were quercetin-3-O-rutinoside, quercetin-3-O-glucoside and quercetin-3-O-glucuronide, with a typical fragment of $MS^1 m/z$ 301 and isorhamnetin-3-O-glucuronide with a typical fragment of $MS^1 m/z$ 315, as reported by [Wasli, Jelali, Silva, Ksouri, and](#)

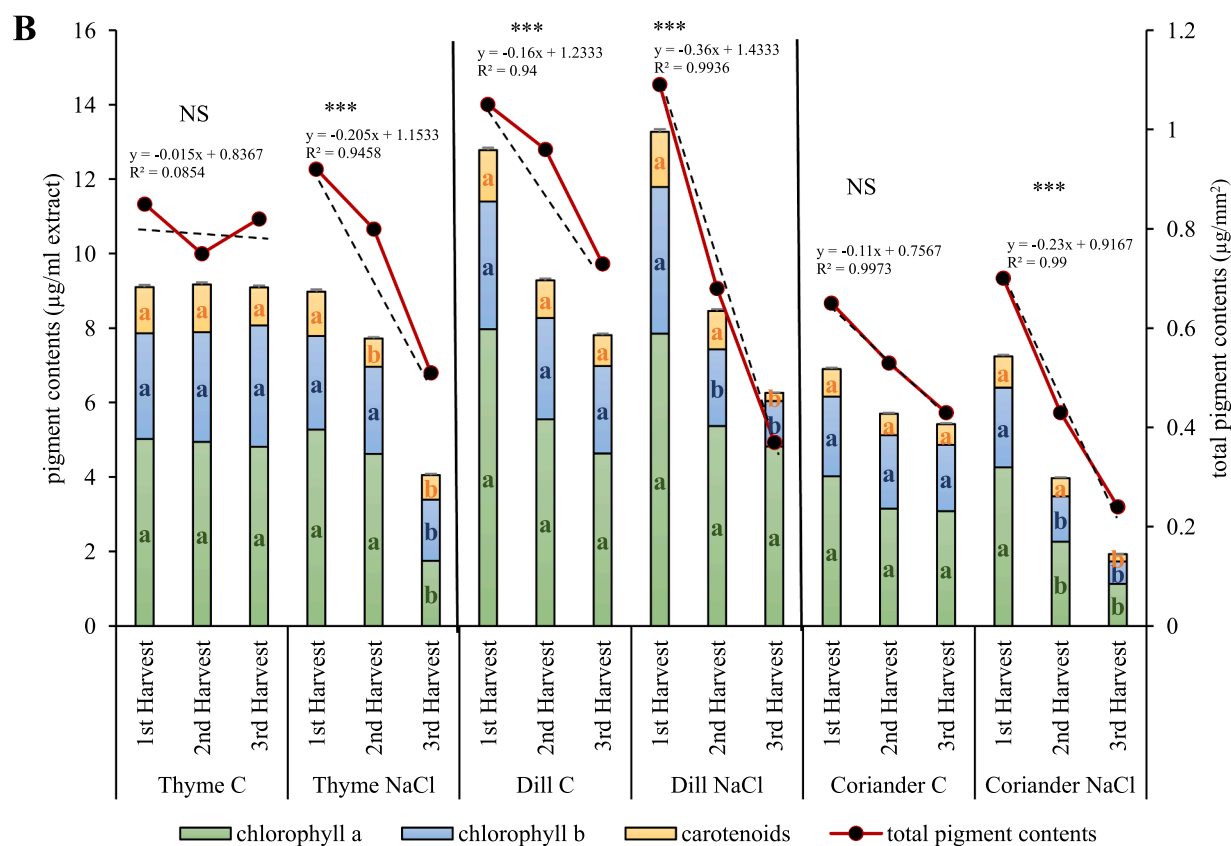
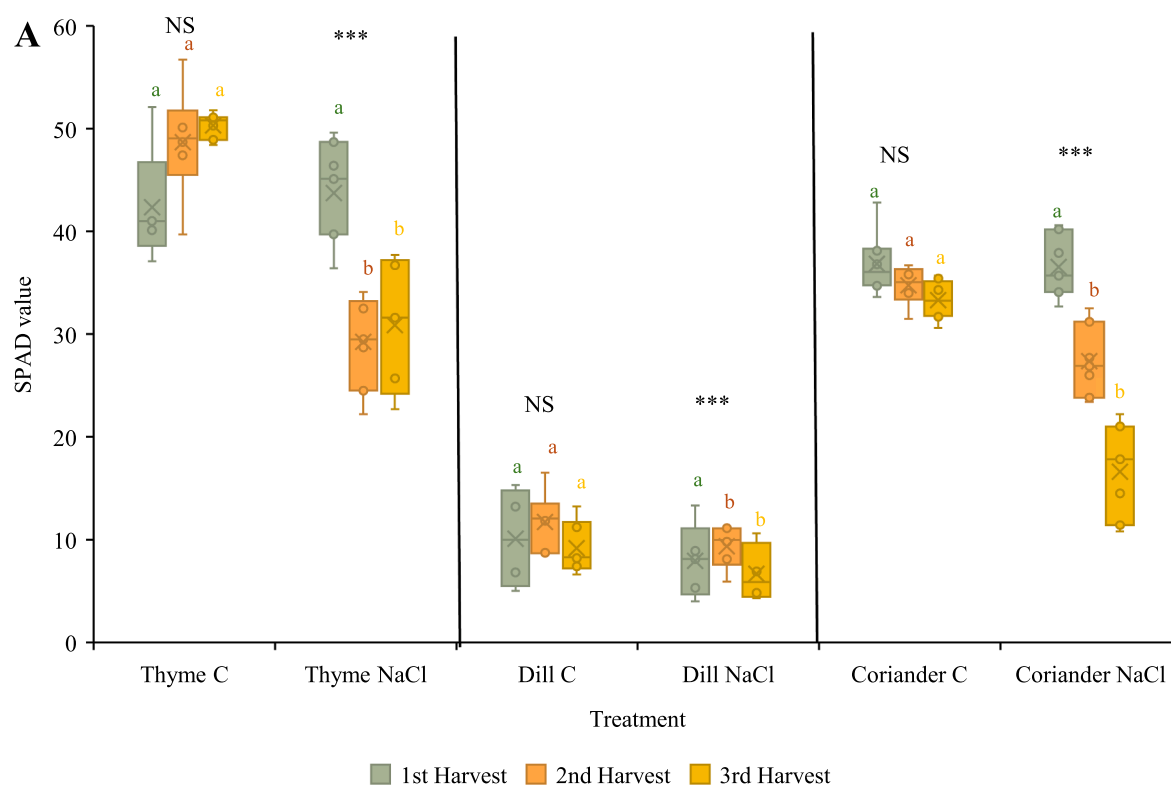


Fig. 2. SPAD value (A), individual pigment contents (µg/ml extract) and total pigment contents (µg/mm²) (B) of herbs under control (C) and saline (NaCl) conditions for three harvest times (1st, 2nd and 3rd). Lowercase letters (a-b) denote statistical differences among control and saline conditions for each herb species under the same harvest date. NS, ***, denote statistical differences among harvest dates within the same species and treatment.

Table 1
Tentative identification of phenolic compounds in thyme.

Compound	Rt (min)	[M-H] ⁻ (m/z)	MS ² (m/z)	MS ³ (m/z)
Syringic acid hexoside 1	7.84	395	359 (100)	197 (100)
Syringic acid hexoside 2	9.73	359	197 (100)	—
Quercetin-3-O-rutinoside	11.40	465	303 (100)	—
Apigenin-6,8-di-O-glucoside	14.96	593	473 (100), 503 (70)	—
Eriodictyol-O-hexoside 1	16.93	449	287 (100)	—
Rosmarinic acid	17.00	377	359 (100)	161 (100), 179 (26), 197 (23), 223 (14)
Kaempferol-3-O-hexoside	19.09	447	285 (100)	—
Eriodictyol-O-hexoside 2	20.17	449	287 (100), 269 (24)	—
Luteolin-3-O-hexuronide	22.66	461	285 (100)	—
Sagerinic acid	24.45	719	557 (100), 359 (30)	359 (100), 161 (80), 179 (29), 197 (23), 223 (15)
Salvianolic acid A	26.01	537	493 (100)	—
Salvianolic acid	26.83	493	359 (100)	—
Salvianolic acid A dimer	27.81	555	493 (100), 359 (29)	—
Salvianolic acid 1 isomer	28.04	569	537 (100), 493 (24)	—
Salvianolic acid B derivative	30.29	717	519 (100), 537 (52), 673 (43), 493 (7)	—

Rt = retention time; [M-H]⁻ = main mass of substance in negative ion mode; MS² = first fragmentation; MS³ = second fragmentation.

Table 2
Tentative identification of phenolic compounds in dill.

Compound	Rt (min)	[M-H] ⁻ (m/z)	MS ² (m/z)
Chlorogenic acid	9.25	353	191 (100), 179 (60), 173 (23)
Chlorogenic acid derivative 1	10.25	353	191 (100), 179 (60), 173 (23)
Neochlorogenic acid	11.04	353	191 (100), 179 (70), 135 (21)
Chlorogenic acid derivative 2	11.93	353	191 (100), 179 (60), 173 (23)
Chlorogenic acid derivative 3	13.18	353	191 (100), 179 (60), 173 (23)
Chlorogenic acid derivative 4	13.92	353	191 (100), 179 (60), 173 (23)
Neochlorogenic acid derivative	14.10	353	191 (100), 179 (70), 135 (21)
Quercetin-3-O-rutinoside	20.11	609	301 (100)
Quercetin-3-O-glucoside	20.93	463	301 (100), 300 (70)
Quercetin-3-O-glucuronide	22.65	477	301 (100)
Isorhamnetin-3-O-glucuronide	23.89	491	315 (100)

Rt = retention time; [M-H]⁻ = main mass of substance in negative ion mode; MS² = first fragmentation; MS³ = second fragmentation.

Cardoso (2018).

In coriander, 8 individual phenolics were identified: four hydroxycinnamic acid derivatives, two flavonols and two flavones (Table 3). The hydroxycinnamic acid were identified as chlorogenic acid and chlorogenic acid isomer with the fragmentation pattern of MSⁿ *m/z* 191, 179, 173, as reported by Barros *et al.* (2012). neochlorogenic acid was identified based on the typical fragmentation pattern of MSⁿ *m/z* 191, 179, 135, as reported by Abdallah *et al.* (2024). Dimethoxycinnamoyl

Table 3
Tentative identification of phenolic compounds in coriander.

Compound	Rt (min)	[M-H] ⁻ (m/z)	MS ² (m/z)	MS ³ (m/z)
Chlorogenic acid	13.22	353	191 (100), 179 (60), 173 (23)	—
Chlorogenic acid isomer	14.96	353	191 (100), 179 (60), 173 (23)	—
Dimethoxycinnamoyl hexoside	16.76	739	369 (100)	189 (100), 207 (16)
Neochlorogenic acid	18.59	353	191 (100), 179 (70), 135 (21)	—
Quercetin-3-O-rutinoside	20.22	609	301 (100)	—
Apigenin hexoside 1	21.84	451	221 (100), 365 (99)	—
Quercetin-3-O-glucuronide	22.65	477	301 (100)	—
Apigenin hexoside 2	24.50	451	431 (100), 227 (30)	—

Rt = retention time; [M-H]⁻ = main mass of substance in negative ion mode; MS² = first fragmentation; MS³ = second fragmentation.

hexoside was identified based on the fragment of MSⁿ *m/z* 189, 207, as reported by Barros *et al.* (2012). The two flavonols were quercetin-3-O-rutinoside and quercetin-3-O-glucuronide, with a typical fragment of MSⁿ *m/z* 301 as reported by Wasli *et al.* (2018). The two flavones were apigenin hexoside 1 and apigenin hexoside 2 with typical fragmentation of MSⁿ *m/z* 221,361,431 and 227, as reported by Barros *et al.* (2012).

3.3.2. Quantification of phenolic compounds in salt grown herbs

The content of phenolic compounds groups in all three herb species are presented in Fig. 3(A, B, C). In all three herbs, the harvest date had a significant impact on phenolic contents. In thyme C, phenolic acids represented 75.0 %, flavonoids 9.1 % and flavanones 15.8 % of total phenolic content, while in thyme NaCl phenolic acids represented 75.4 %, flavonoids 7.7 % and flavanones 16.8 %. Phenolic acid content decreased 41.2 % at the 2nd harvest date and 7.9 % at the 3rd harvest date in thyme NaCl, compared to the C treatment. Flavonoid content in thyme NaCl decreased for 32.6 % and 45.3 %, at the 2nd and 3rd harvest, respectively, compared to the thyme C treatment.

In thyme, the most abundant individual phenolics were sagerinic acid and salvianolic acid (Suppl. Table 1). We observed a significant decrease in most individual phenolics under saline conditions which ranged from 9.7 % to 56.5 %, being especially pronounced at the 3rd harvest date. The only increase under saline conditions was at 1st harvest date in the content of eriodictyol-O-hexoside 1, which increased for 37.3 %, and salvianolic acid B derivative, which increased for 58.8 % when compared to the C treatment.

In dill C, phenolic acids represented 90.4 % and flavonoids 9.5 %, while in dill NaCl, phenolic acids represented 90.1 % and flavonoids 9.9 % of the total phenolic content. Phenolic acids in dill NaCl decreased by 22.6 % at the 1st harvest date, compared to the C treatment. Flavonoid content of dill NaCl decreased at the 1st and 2nd harvest dates for 24.3 % and 23.6 %, respectively, when compared to the dill C treatment. In dill, the most abundant individual phenolics were chlorogenic acid and neochlorogenic acids (Suppl. Table 2). Chlorogenic acid increased at the 2nd harvest date for 64.6 %, when compared to the dill C treatment. Apigenin hexoside 1 content was higher in dill NaCl than in C treatment at all three harvest dates by 25.0 %, 75.7 % and 66.5 % respectively.

In coriander C, phenolic acids represented 72.4 % and flavonoids 27.6 %, and in coriander NaCl phenolic acids represented 75.8 % and flavonoids 24.1 % of total phenolic content. Phenolic acids in coriander NaCl decreased by 29.4 % at the 1st harvest date, compared to the coriander C treatment. Flavonoids in coriander NaCl decreased by 54.3 % at the 3rd harvest date, compared to the coriander C treatment. In coriander, the most abundant individual phenolics were chlorogenic

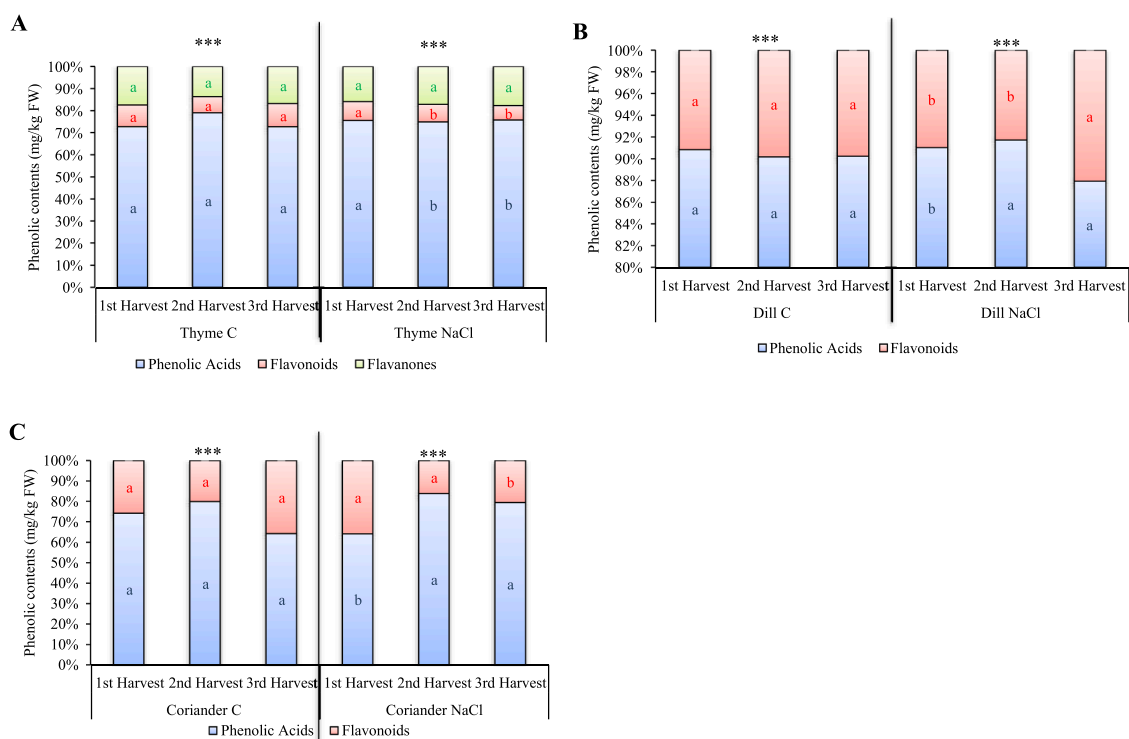


Fig. 3. Phenolic contents (mg/kg FW) of thyme (A), dill (B) and coriander (C) under control (C) and saline (NaCl) conditions for three harvest times (1st, 2nd and 3rd). Lowercase letters (a-b) denote statistical differences among control and saline conditions for each species of herb under the same harvest date. NS, ***, denote statistical differences among harvest dates within the same species and treatment.

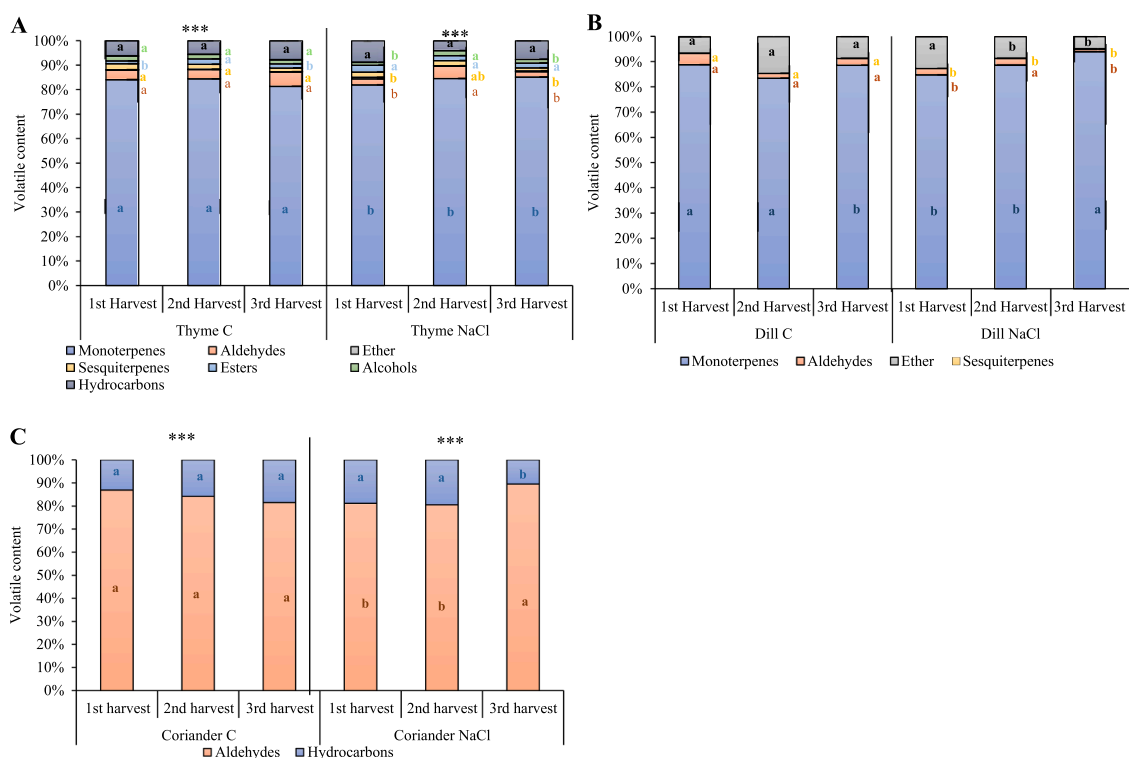


Fig. 4. Volatile contents (mg/kg FW) of thyme (A), dill (B) and coriander (C) under control (C) and saline (NaCl) conditions for three harvest times (1st, 2nd and 3rd). Lowercase letters (a-b) denote statistical differences among control and saline conditions for each species of herb under the same harvest date. NS, ***, denote statistical differences among harvest dates within the same species and treatment.

acid derivative 3 and isorhamnetin-3-O-glucuronide (Suppl. Table 3). Quercetin-3-O-glucuronide content was higher in coriander NaCl than in C treatment at all three harvest dates by 33.4 %, 71.5 % and 51.2 % respectively. Quercetin-3-O-rutinoside increased significantly at the 3rd harvest date in coriander NaCl treatment, with 45.4 %, compared to the coriander C treatment. Chlorogenic acid derivative 2 was higher in coriander NaCl than in the C treatment at all three harvest dates by 39.6 %, 17.3 % and 55.5 % respectively.

3.4. Total and individual volatile compounds in salt grown herbs

Volatile groups determined in the three herb species are presented in Fig. 4(A, B, C). In all three herbs, harvest date had a significant effect on the volatile content. In thyme, the most abundant group were monoterpenes, which represented >80 % of the total volatile content. Other detected groups of volatiles were aldehydes, ethers, sesquiterpenes, esters, alcohols and hydrocarbons. In general, the volatile content decreased in the NaCl treatment when compared to the C treatment. Monoterpenes in the NaCl treatment decreased for 37.2 % at the 1st, 11.9 % at the 2nd and 13.8 % at the 3rd harvest date, respectively. Interestingly, esters increased by 36.7 % in NaCl treatment at the 1st harvest date when compared to the C treatment and for 7.3 % at the 3rd harvest date, respectively. In thyme, 30 individual volatiles were identified (Suppl. Table 4). At the 1st harvest, Thyme NaCl exhibited significantly higher levels of carvacrol (78.7 %) compared to the C treatment. γ -terpinene, one of the most abundant volatile compounds in thyme, was significantly lower (ranging from 21.3 % to 61.0 %) in the NaCl-treated plants across all harvests, compared to the C treatment. Thymol was significantly lower at the 1st harvest date at the NaCl treatment (40.9 %), when compared to the C treatment. At the 2nd harvest, the content of thymol was higher at the NaCl treatment with 26.1 %, compared to the C treatment, while at the 3rd harvest, no differences were determined. Linalool was significantly increased at the NaCl treatment in the 1st and 2nd harvest compared to the C treatment. α -terpinene and sabinene contents were significantly lower at all three harvest dates in NaCl thyme, compared to the C treatment.

In dill, four volatile groups were determined, namely monoterpenes, aldehydes, ethers and sesquiterpenes. Monoterpenes comprised from 83 % to 94 % of total volatiles content in dill. The second large group were ethers with 4.9 % to 14.5 % of total volatiles content. In dill NaCl, monoterpenes decreased at the 1st (22.2 %) and 2nd (11.3 %) harvest date, but increased at the 3rd (36.5 %), when compared to the C treatment. Sesquiterpenes were lower at all three harvest dates (ranging from 28 % to 40 %) in dill NaCl, when compared to the C treatment. A similar trend was also observed in aldehydes and ethers, with the only exception in the 2nd harvest date for aldehydes and 1st harvest date for ethers, where no differences were observed among C and NaCl treatments. In dill, 13 individual volatiles were identified (Suppl. Table 5). α -phellandrene, the most abundant volatile in dill, decreased at the 1st and 2nd harvest dates in NaCl-treated dill, but increased at the 3rd harvest date by 27.2 %, when compared to the C treatment. Similarly, limonene also decreased at the 2nd harvest, and increased at the 3rd harvest date. Dill ether content was 36.2 % higher at the 1st harvest of the NaCl treatment, but at the 2nd and 3rd harvests, it decreased for 50.5 % and 26.8 %, respectively, compared to the C treatment. Other volatiles, like *p*-cymene and β -phellandrene, varied greatly among harvest dates and treatments.

In coriander, the two most abundant groups of volatiles were aldehydes (80.5 % to 89.5 %) and hydrocarbons (10.5 % to 19.5 %). Aldehydes were significantly lower at the first two harvest dates in NaCl-treated coriander (1st harvest date 16.8 %, 2nd harvest date 20.4 %), compared to the C treatment. Hydrocarbons were significantly lower at the 3rd harvest date, with 43.2 %, compared to the C treatment. In coriander, 11 individual volatiles were identified (Suppl. Table 6). 2E-decenal (the most abundant volatile) content was lower for 18.9 % in the NaCl treatment 1st harvest, but at the 3rd harvest date, the content

was significantly higher for 37.0 % in the NaCl treatment, compared to the C treatment. Decanal was lower at the 2nd harvest date in coriander NaCl when compared to the C treatment. Methyl-cyclopentane decreased significantly at the 3rd harvest date for 34.1 % in NaCl coriander, compared to the C treatment.

3.5. PAL and POX activity in salt grown herbs

The enzymatic activity of thyme, dill and coriander are presented in Fig. 5(A, B). In all treatments, harvest date had a significant impact on the enzymatic activity. In thyme, PAL activity was higher (58.3 %) at the 1st harvest NaCl treatment compared to the C treatment. At the 2nd harvest date, the activity was higher at the C treatment, and at the 3rd harvest, no changes were observed. In general, thyme showcased the highest PAL activity of all three herbs and the lowest POX activity. POX activity showed statistically significant differences at the 1st harvest date in thyme NaCl, compared to the C treatment. The other two harvest dates showed no difference regarding POX activity.

In dill, PAL activity did not statistically vary among C and NaCl treatments. On the other hand, POX activity was significantly higher at NaCl at the 1st and 2nd harvest dates, when compared to the C treatment, with 31.1 % and 32.8 % respectively.

In coriander, at the 3rd harvest date, NaCl treatment had 37.5 % lower PAL activity than C treatment. POX activity in coriander increased at each harvest date, with its activity reaching peak at the 3rd harvest. Statistically significant differences were observed at the 2nd and 3rd harvest, with the NaCl treatment having 41.0 % and 32.7 % lower activity than the C treatment.

4. Discussion

The cultivation of thyme, dill and coriander was undertaken in a hydroponic system under saline conditions. The yield exhibited a substantial decline under saline conditions, across all three herbs. This finding is consistent with the results reported by [Atta et al. \(2023a\)](#), who observed a substantial decline in yield in plants subjected to salt stress. A similar effect of salinity on the yield was also observed by [Khalid and Cai \(2011\)](#) in *Melissa officinalis* L. (lemon balm) and in *Ocimum basilicum* L. (basil) as reported by [Zamljen et al. \(2024\)](#).

The effect of salinity on dry weight exhibited variation among different herb species, with thyme demonstrating an increase in dry weight content, particularly at the second and third harvests. This finding contradicts the results reported by [Bistgani et al. \(2019\)](#), who observed a decrease in dry weight in salt-stressed thyme. Conversely, coriander exhibited a decline in dry weight under saline conditions at the third harvest date, a finding that aligns with the results reported by [Bistgani et al. \(2019\)](#). Sodium chloride (NaCl) has been demonstrated to interfere with the absorption of water and essential nutrients by plants, resulting in ion toxicity, osmotic and oxidative stress, altered metabolic pathways, and reduced turgor pressure. These phenomena have been shown to impact the yield and dry matter of herbs, thus underscoring the need for further research in this area. Furthermore, an elevated concentration of salt ions has been demonstrated to exert deleterious effects on the photosynthetic apparatus, inducing chlorosis and promoting premature senescence ([Hanin, Ebel, Ngom, Laplaze, and Masmoudi, 2016](#)). This assertion is corroborated by our SPAD and pigment content results, which exhibited a declining trend in all three herbs under saline conditions. This effect is responsible for a concomitant decrease in yield, as evidenced in our case study. Salinity has been demonstrated to disrupt the photosynthetic electron transport chain, thereby increasing the production of reactive oxygen species (ROS) within plant cells. This, in turn, has been shown to lead to photooxidative damage ([Akyol, Yilmaz, UZİLDAY, Uzılday, and Türkan, 2020](#)).

It was observed that dill was less affected by salt at the initial harvest date. This finding suggests that it may possess a higher level of tolerance to salinity compared to the other two herb species. Additionally, it

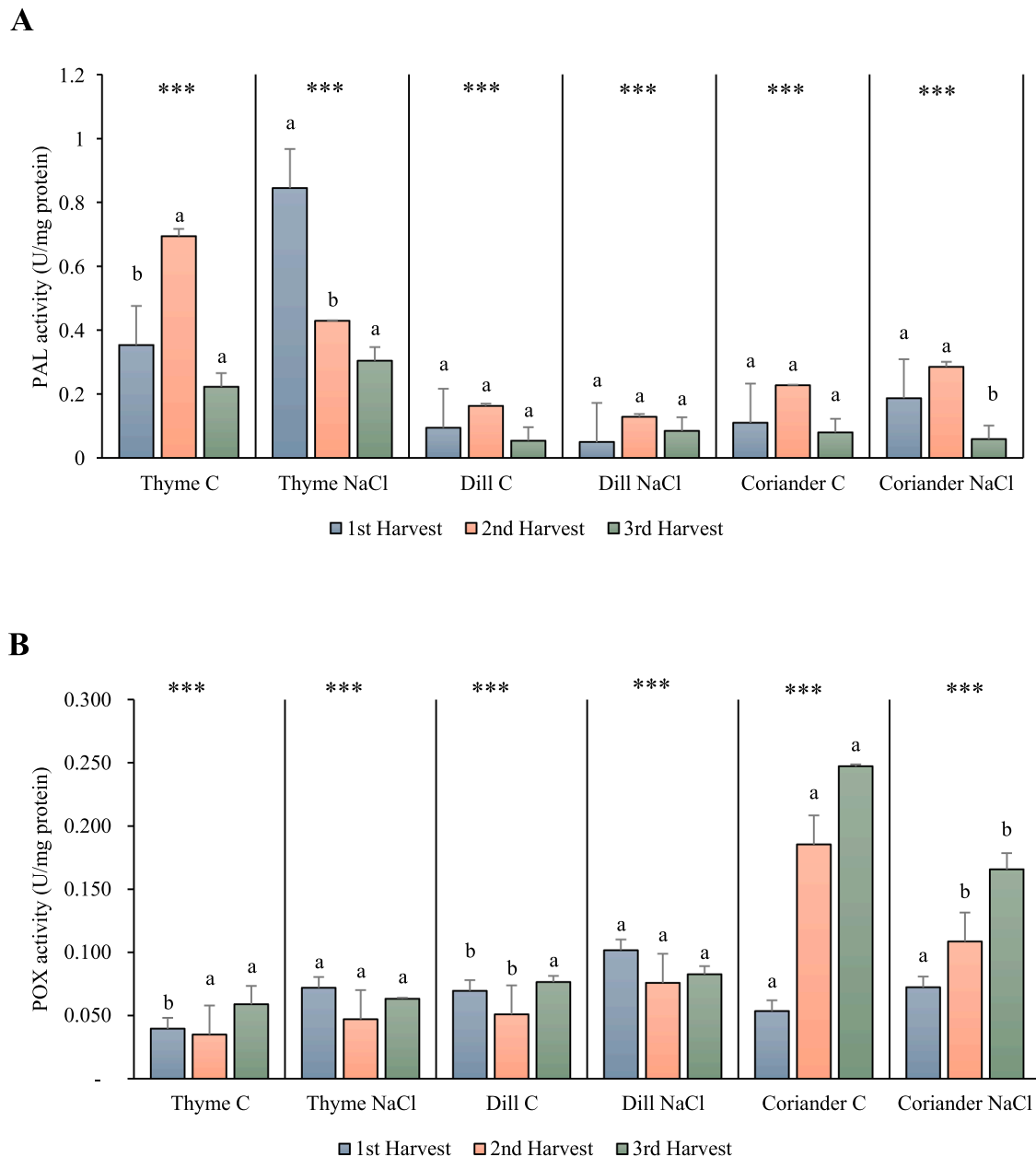


Fig. 5. Activity of phenylalanine ammonia lyase - PAL (A) and peroxidase - POX (B) enzymes of thyme, dill and coriander under control (C) and saline (NaCl) conditions for three harvest times (1st, 2nd and 3rd). Lowercase letters (a-b) denote statistical differences among control and saline conditions for each species of herbs under the same harvest date. NS, ***, denote statistical differences among harvest dates within the same species and treatment.

appears to effectively prevent excessive salt ion accumulation in tissues, which could potentially lead to ion toxicity (Kaleem *et al.*, 2018).

In order to mitigate the effects of salinity and the increase of ROS in cells, plants have been observed to undergo changes in the metabolic pathways and the synthesis of defense molecules. A decline in phenolics was observed in herbs cultivated under salt stress, particularly as the harvest date progressed. As demonstrated by (Nazari, Ghasemi-Soloklui, Kordrostami, and Abdel Latif, 2023), phenolics are typically accumulated by plants as defense molecules. However, this was not observed in the present case. A comparable outcome was observed in the context of volatiles, which exhibited a decline with advancing harvest dates under saline conditions. However, an exception was noted for dill, where a notable increase in monoterpenes (especially α -pinene, limonene, myrcene, linalool) was observed at the third harvest date under saline conditions.

One potential explanation for this outcome is that the initial enzyme

activity of PAL at 1st harvest was elevated under saline conditions, as observed in thyme. However, due to the elevated salinity level of 100 mM, the metabolic processes of the plants were disrupted under prolonged stress, leading to a reduction of phenolic synthesis. In addition, no alterations were detected in PAL activity in several instances, with the exception of thyme (1st and 2nd harvest) and dill (1st and 2nd harvest). However, saline conditions appeared to enhance POX activity in comparison to the control, suggesting a potential defensive mechanism employed by the herbs growing in elevated salinity levels. This observation aligns with the findings reported by Wu *et al.* (2022). In the case of coriander, the activity of POX was found to be lower under saline conditions than in C conditions. This suggests that coriander may have a less effective defense mechanism against salt stress. The second explanation may be that the decrease in phenolic content could be due to scavenging of excessive ROS under high salinity, as reported by Hanin *et al.* (2016) and Aboul-Enein, Kruk, Kładna, Lichszteid, and Michalska

(2007).

The content of volatile compounds was found to decrease with increasing duration of the salt stress (harvest dates), a finding which was also reported in 100 mM NaCl-grown basil (Zamljen *et al.*, 2024). In the context of saline stress, significant alterations in the volatile profiles of herbs such as thyme, dill, and coriander have been observed. These alterations are characterized by an increased biosynthesis of monoterpenes, which play a pivotal role in the plant's stress defense mechanisms (Mariola and Feder-Kubis, 2020). In thyme, key volatiles such as thymol, carvacrol, *p*-cymene, and γ -terpinene mostly increase, contributing to the antioxidant. In response to this, dill exhibits elevated levels of carvone, limonene, and α -phellandrene, while coriander demonstrates increased accumulation of linalool, geranyl acetate, and camphor (Tsamaidi, Daferera, Karapanos, and Passam, 2017). These volatiles have been shown to play a critical role in mitigating oxidative damage and enhancing plant resilience under salinity (Thangaleela *et al.*, 2022). In the present study, the volatile content exhibited significant variability. A considerable number of volatiles, including thymol and γ -terpinene, demonstrated a decline, likely attributable to the elevated level of salinity and the protracted duration of the stress period. This assertion is supported by the findings of DiCara and Gedan (2023), who emphasized that the intensity and duration of stress exerted a pivotal influence on plant production outcomes.

5. Conclusion

Collectively, these findings emphasize the intricate and time-dependent effects of salinity stress on the quality and quantity parameters of thyme, dill and coriander. Extended exposure to 100 mM NaCl has been demonstrated to exert detrimental effects on the investigated herbs. These results provide valuable insights for the refinement of cultivation strategies, indicating that the application of 100 mM NaCl may be advantageous only when restricted to short-term use in herb production, particularly within hydroponic systems, in order to maximize yield quality. The results of this study are of crucial importance for the production of herbs in Slovenia and Europe, since the significance of herbs extends beyond their culinary applications. Indeed, they play an important role in agriculture, traditional medicine, and modern research on plant resilience and bioactive compounds.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Tilen ZAMLJEN: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Robert VEBERIC:** Writing – review & editing, Project administration, Funding acquisition. **Mariana Cecilia GROHAR:** Writing – review & editing, Software, Resources, Methodology, Investigation, Data curation.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2025.114445.

Data availability

Data will be made available on request.

References

- Abdallah, R.H., Hassan, W.H.B., Al-Massarani, S.M., Abdel-Mageed, W.M., Eldahmy, S.I., Basudan, O.A., ... Abdelaziz, S. (2024). UPLC-ESI-MS/MS profiling of secondary metabolites from methanol extracts of *In Vivo* and *In vitro* tissues of *Daucus capillifolius* Gilli (A Comparative Study). 29(11), 2694.
- Aboul-Enein, H.Y., Kruk, I., Kladna, A., Lichszeld, K., & Michalska, T. (2007). Scavenging effects of phenolic compounds on reactive oxygen species. 86(3), 222–230. doi:https://doi.org/10.1002/bip.20725.
- Ahmadi, H., Fatahi, R., Zamani, Z., Pocai, P., Shokrpour, M., 2024. Unraveling the transcriptional regulators of polyphenolic variation in *Thymus daenensis* Celak. Ind. Crops. Prod. 214, 118551. https://doi.org/10.1016/j.indcrop.2024.118551.
- Akyol, T.Y., Yilmaz, O., UZILDAY, B., Uzilday, R.O., Türkan, I., 2020. Plant response to salinity: an analysis of ROS formation, signaling, and antioxidant defense. Turkish. J. Bot. 44 (1), 1–13.
- Atta, K., Mondal, S., Gorai, S., Singh, A.P., Kumari, A., Ghosh, T., ... Jespersen, D. (2023a). Impacts of salinity stress on crop plants: improving salt tolerance through genetic and molecular dissection. Volume 14 - 2023. doi:10.3389/fpls.2023.1241736.
- Atta, K., Mondal, S., Gorai, S., Singh, A.P., Kumari, A., Ghosh, T., ... Jespersen, D. (2023b). Impacts of salinity stress on crop plants: improving salt tolerance through genetic and molecular dissection. 14. doi:10.3389/fpls.2023.1241736.
- Babotă, M., Frumuzachi, O., Nicolescu, A., Dias, M.I., Pinela, J., Barros, L., ... Crişan, G. (2023). *Thymus* species from Romanian spontaneous flora as promising source of phenolic secondary metabolites with health-related benefits. 12(2), 390.
- Baretseng, S.J.J.I. (2022). The worldwide herbal market: trends and opportunities. 2766, 2276.
- Barros, L., Dueñas, M., Dias, M.I., Sousa, M.J., Santos-Buelga, C., Ferreira, I.C.F.R., 2012. Phenolic profiles of *in vivo* and *in vitro* grown coriandrum sativum L. Food. Chem. 132 (2), 841–848. https://doi.org/10.1016/j.foodchem.2011.11.048.
- Bistgani, Z.E., Hashemi, M., DaCosta, M., Craker, L., Maggi, F., Morshedloo, M.R., 2019. Effect of salinity stress on the physiological characteristics, phenolic compounds and antioxidant activity of *Thymus vulgaris* L. and *Thymus daenensis* Celak. Ind. Crops. Prod. 135, 311–320. https://doi.org/10.1016/j.indcrop.2019.04.055.
- Čulina, P., Cvitković, D., Pfeifer, D., Zorić, Z., Repajić, M., Elez Garofulić, I., ... Padišić, S. (2021). Phenolic profile and antioxidant capacity of selected medicinal and aromatic plants: diversity upon plant species and extraction technique. 9(12), 2207.
- Čavar Zeljković, S., Aucique-Perez, C.E., Štefelová, N., De Diego, N., 2022. Optimizing growing conditions for hydroponic farming of selected medicinal and aromatic plants. Food. Chem. 375, 131845. https://doi.org/10.1016/j.foodchem.2021.131845.
- DiCara, C., & Gedan, K. (2023). Distinguishing the effects of stress intensity and stress duration in plant responses to salinity. 12(13), 2522.
- Foss, K., Przybyłowicz, K.E., Sawicki, T., 2022. Antioxidant activity and profile of phenolic compounds in selected herbal plants. Plant. Foods. Hum. Nutr. 77 (3), 383–389. https://doi.org/10.1007/s11130-022-00989-w.
- Gantait, S., Sharangi, A.B., Mahanta, M., Meena, N.K., 2022. Agri-biotechnology of coriander (*Coriandrum sativum* L.): an inclusive appraisal. Appl. Microbiol. Biotechnol. 106 (3), 951–969. https://doi.org/10.1007/s00253-022-11787-4.
- Hallmann, E., & Sabała, P. (2020). Organic and conventional herbs quality reflected by their antioxidant compounds concentration. 10(10), 3468.
- Hanin, M., Ebel, C., Ngom, M., Laplaze, L., Masmoudi, K., 2016. New insights on plant salt tolerance mechanisms and their potential use for breeding. J. Front. Plant. Sci. 7, 1787.
- Hussain, A., Arif, M.R., Ahmed, A., Fiaz, I., Zulfikar, N., Ali, M.Q., ... Elkhedir, A.E. (2024). Evaluation of leaves, flowers, and seeds of coriander (*Coriandrum sativum* L.) through microwave drying and ultrasonic-assisted extraction, for biologically active components. 2024(1), 2378604. doi:https://doi.org/10.1155/2024/2378604.
- Kacjan Marsič, N., Štolfa, P., Vodnik, D., Košmelj, K., Mikulić-Petkovšek, M., Kump, B., ... Šircelj, H. (2021). Physiological and biochemical responses of ungrafted and grafted bell pepper plants (*Capsicum annuum* L. var. *grossum* (L.) sendtn.) Grown under moderate salt stress. 10(2), 314.
- Kaleem, F., Shabir, G., Aslam, K., Rasul, S., Manzoor, H., Shah, S.M., Khan, A.R., 2018. An overview of the genetics of plant response to salt stress: present status and the way forward. Appl. Biochem. Biotechnol. 186 (2), 306–334. https://doi.org/10.1007/s12010-018-2738-y.
- Kaur, G., Sanwal, S.K., Kumar, A., Pundir, R.K., Yadav, M., Sehrawat, N., 2024. Role of osmolytes dynamics in plant metabolism to cope with salinity induced osmotic stress. Discov. Agric. 2 (1), 59. https://doi.org/10.1007/s44279-024-00070-x.
- Khalid, K.A., Cai, W., 2011. The effects of mannitol and salinity stresses on growth and biochemical accumulations in lemon balm. Shengtai. Xuebao/Acta. Ecol. Sin. 31 (2), 112–120. https://doi.org/10.1016/j.chnaes.2011.01.001.
- Krsnik, S., Erjavec, K., 2024. Factors influencing use of medicinal herbs. J. Patient. Exp. 11, 23743735241241181. https://doi.org/10.1177/23743735241241181.

- Lungoci, C., Motrescu, I., Filipov, F., Jitareanu, C.D., Teliban, G.-C., Ghitau, C.S., ... Robu, T. (2022). The impact of salinity stress on antioxidant response and bioactive compounds of *nepeta cataria* L. 12(3), 562.
- Macaluso, D., Licciardo, F., Carbone, K., 2024. Farming of medicinal and aromatic plants. *Struct. Features. Econ. Results* 14 (1), 151.
- Mariola, Z.-B., Feder-Kubis, J., 2020. Monoterpenes and their derivatives—recent development in biological and medical applications. *Int. J. Mol. Sci* 21, 7078. <https://doi.org/10.3390/ijms21197078>.
- Narayana, D.B.A., Brindavanam, N.B., Shirsekar, S., 2024. History of safe use of herbs - approaches for documenting evidence. *J. Ayurveda. Integr. Med* 15 (1), 100849. <https://doi.org/10.1016/j.jaim.2023.100849>.
- Nazari, M., Ghasemi-Soloklui, A.A., Kordrostami, M., Abdel Latef, A.A.H., 2023. Deciphering the response of medicinal plants to abiotic stressors: a focus on drought and salinity. *Plant. Stress* 10, 100255. <https://doi.org/10.1016/j.stress.2023.100255>.
- Parida, A.K., Das, A.B., 2005. Salt tolerance and salinity effects on plants: a review. *Ecotoxicol. Env. Saf* 60 (3), 324–349. <https://doi.org/10.1016/j.ecoenv.2004.06.010>.
- Seyedi, F.S., Nafchi, M.G., Reezi, S., 2024. Effects of light spectra on morphological characteristics, primary and specialized metabolites of *Thymus vulgaris* L. *Heliyon* 10 (1). <https://doi.org/10.1016/j.heliyon.2023.e23032>.
- Shanila, S., S. G., Nair, D.S., Stephen, R., Gopinath, P.P., 2024. Hydroponic cultivation of spices and aromatics: techniques, benefits and challenges. *Int. J. Environ. Clim. Change* 14 (11), 234–254. <https://doi.org/10.9734/ijec/2024/v14i114542>.
- Shyu, Y.-S., Lin, J.-T., Chang, Y.-T., Chiang, C.-J., Yang, D.-J., 2009. Evaluation of antioxidant ability of ethanolic extract from dill (*Anethum graveolens* L.) flower. *Food. Chem* 115 (2), 515–521. <https://doi.org/10.1016/j.foodchem.2008.12.039>.
- Simkova, K., Veberic, R., Hudina, M., Grohar, M.C., Ivancic, T., Smrke, T., Jakopic, J., 2023a. Berry size and weight as factors influencing the chemical composition of strawberry fruit. *J. Food. Compos. Anal.* 123, 105509. <https://doi.org/10.1016/j.jfca.2023.105509>.
- Simkova, K., Veberic, R., Hudina, M., Grohar, M.C., Ivancic, T., Smrke, T., ... Jakopic, J. (2023b). Variability in 'Capri' Everbearing strawberry quality during a harvest season. 12(6), 1349.
- Thangaleela, S., Sivamaruthi, B.S., Kesika, P., Tiyyajamorn, T., Bharathi, M., & Chaiyasut, C. (2022). A narrative review on the bioactivity and health benefits of Alpha-Phellandrene. 90(4), 57.
- Tsamaidi, D., Daferera, D., Karapanos, I., Passam, H., 2017. The effect of water deficiency and salinity on the growth and quality of fresh dill (*Anethum graveolens* L.) during autumn and spring cultivation. *Int. J. Plant. Prod.* 11, 33–46.
- Wasli, H., Jelali, N., Silva, A.M.S., Ksouri, R., Cardoso, S.M., 2018. Variation of polyphenolic composition, antioxidants and physiological characteristics of dill (*Anethum graveolens* L.) as affected by bicarbonate-induced iron deficiency conditions. *Ind. Crops. Prod* 126, 466–476. <https://doi.org/10.1016/j.indcrop.2018.10.007>.
- Wellburn, A.R., 1994. The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. *J. Plant. Physiol* 144 (3), 307–313. [https://doi.org/10.1016/S0176-1617\(11\)81192-2](https://doi.org/10.1016/S0176-1617(11)81192-2).
- Wu, L., Jiang, Q., Zhang, Y., Du, M., Ma, L., & Ma, Y. (2022). Peroxidase activity in tomato leaf cells under salt stress based on micro-hyperspectral imaging technique. 8 (9), 813.
- Zamljen, T., Medic, A., Hudina, M., Veberic, R., & Slatnar, A. (2022). Biostimulatory effects of amino acids on phenylalanine ammonia lyase, capsaicin synthase, and peroxidase activities in *capsicum baccatum* L. 11(5), 674.
- Zamljen, T., Medic, A., Veberic, R., Hudina, M., Grohar, M.C., Slatnar, A., 2023. Influence of hydrolyzed animal protein-based biostimulant on primary, soluble and volatile secondary metabolism of Genovese and Greek-type basil grown under salt stress. *Sci. Hortic* 319, 112178. <https://doi.org/10.1016/j.scienta.2023.112178>.
- Zamljen, T., Zupanc, V., Grohar, M.C., Lojen, S., Slatnar, A., 2024. Effects of hydrolyzed animal protein application on nitrogen translocation, phenolic and volatile profile of *ocimum basilicum* L. under salinity conditions. *Sci. Hortic* 327, 112823. <https://doi.org/10.1016/j.scienta.2023.112823>.