



Solid Residues from the Distillation of Medicinal and Aromatic Plants as Amendments for Acid Soils: A Preliminary Study

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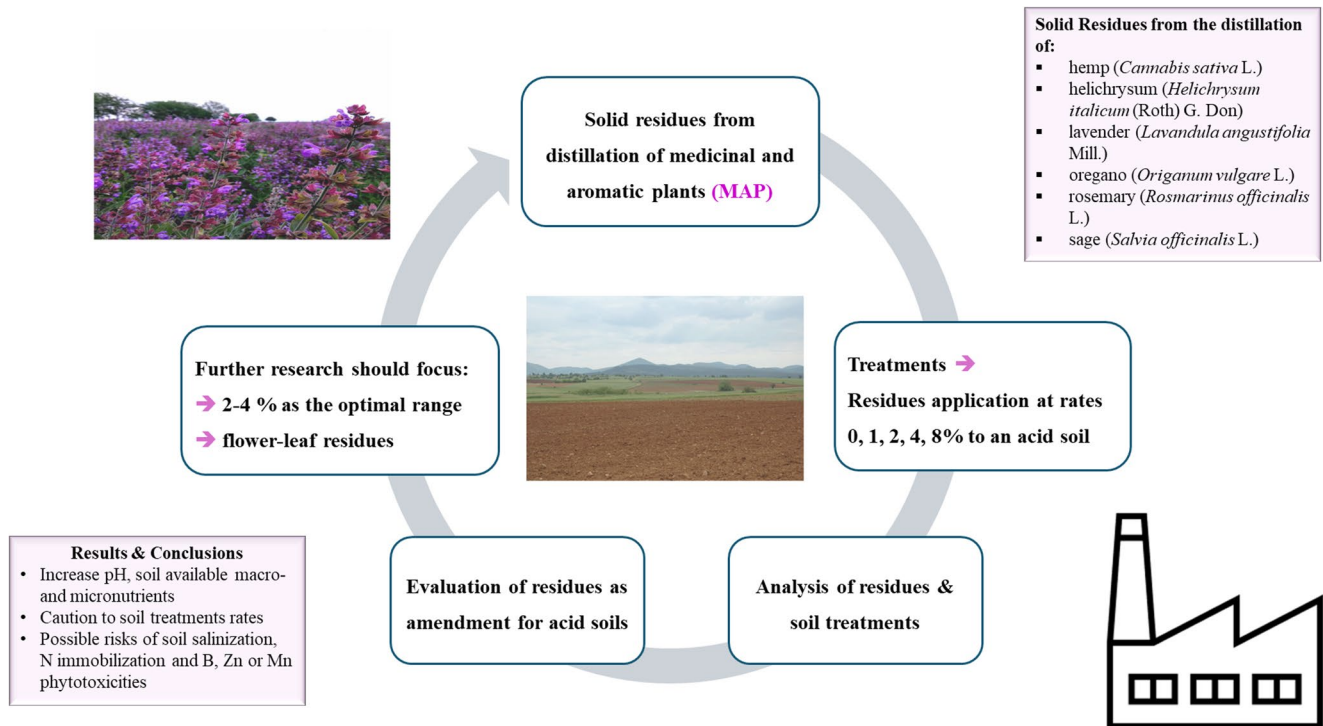
Abstract

Knowledge concerning the use of solid residues from the distillation of medicinal and aromatic plants (MAP) as amendments-fertilizers for acid soils, instead of their combustion or disposal to the environment, is too limited. The aim of the study was a preliminary evaluation of the use of solid residues from the distillation of selected medicinal and aromatic plants as amendments-fertilizers for acid soils. Specifically, in the perspective of further and extensive investigation, the fertilization capacity of solid residues from the distillation of selected MAP was initially realized and the optimal range of application rates of the residues to acid soils was initially determined. From that point of view, the present study was a preliminary study and lasted for six months. Solid residues from the distillation of hemp (*Cannabis sativa* L.), helichrysum (*Helichrysum italicum* (Roth) G. Don), lavender (*Lavandula angustifolia* Mill.), oregano (*Origanum vulgare* L.), rosemary (*Rosmarinus officinalis* L.) and sage (*Salvia officinalis* L.) were collected from industries of essential oils of northern Greece. Then the residues were added to a strongly to moderately acid soil at 0 (control), 1, 2, 4 and 8% rates (treatments), in three replications and the soil treatments were analyzed for chemical properties and fertility indices. pH significantly increased compared with control upon the addition of all residues at the 2% rate and above. Although pH remained acid in all cases, it increased more than one unit in soils treated with 4% and 8% flower-leaf residues from hemp distillation, making soil's reaction slightly acidic. Similar results were obtained for electrical conductivity (EC) and the carbon/nitrogen (C/N) ratio. It is worth noting that EC increased six-ten times upon the 8% application of flower-leaf residues, whereas the C/N ratio increased considerably with the 8% addition of lavender and helichrysum residues. Regarding soil available macronutrients, nitrate-nitrogen (NO₃-N), phosphorus (P) and potassium (K) significantly increased from adequate to high levels compared with control. From the soil available micronutrients, only boron (B), zinc (Zn) and manganese (Mn) consistently affected by the application of residues and significantly increased. It is worth noting the multiple increases of B and Zn in soils treated with 8% residues compared with control, which were somewhat concerning. In almost all treatments, soil available B, Cu and Zn ranged at sufficiency levels, whereas Fe and Mn ranged at high levels. The solid residues from the distillation of the studied MAP, especially the flower-leaf residues, could be used as amendments-fertilizers for acid soils, at application rates between 2 and 4%. Rates lower than 2% are not expected to significantly affect soil properties, whereas rates higher than 4% should be avoided, because of risks of soil salinization, N immobilization and B, Zn and probable Mn phytotoxicities.

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Graphical Abstract



Keywords Bio-fertilizers · Medicinal and aromatic plants · Nutrient recycling · Soil amendments · Solid residues of distillation

1 Introduction

The cultivation of medicinal and aromatic plants (MAP) has increased the recent years because of people's demand to replace industrial additives with natural substances, such as essential oils, in medical, pharmaceutical, cosmetic and food products (Elguea-Culebras et al. 2022; Tsimogiannis et al. 2017). Essential oils are extracted from the particular plants by distillation methods and their amounts range between 0.5 and 8% of the dry biomass of the distilled plant, depending on the plant species (Gavaric et al. 2015; Saha and Basak 2020). Consequently, considerable amounts of solid residues are produced because of MAP distillation (Elguea-Culebras et al. 2022).

According to the principles of circular economy (European Commission 2015), the solid residues from MAP distillation could be considered as raw materials for other industries or elsewhere (European Commission 2015). However, the common management practices for these residues are their combustion and/or disposal on landfills and industrial areas (Singh and Suthar 2012). These practices are not environmentally friendly, since 3–19% of methane (CH₄) emissions worldwide originate from landfills (Deka et al. 2011). In addition, when such means

of disposal are used, the bioactive components which are still found in solid residues from MAP distillation are not recovered (Gavaric et al. 2015; Greff et al. 2021; Moisa et al. 2018; Sanchez-Vioque et al. 2013; Santana-Meridas et al. 2014). Moreover, the same stands for the valuable content of solid residues regarding organic matter and essential nutrients for plant growth, in the perspective of using them in agriculture.

There are studies in recent literature concerning the investigation of solid residues from MAP distillation for collection of valuable components (Scendi et al. 2022; Shanaida et al. 2021), biodiesel production, biopesticides (Saha and Basak 2020), substrates (Bassi et al. 2024) and composts or vermicomposts (Saha and Basak 2020; Zaccardelli et al. 2021). The results showed that there are bioactive compounds (essential oils, flavonoids and phenols) (Scendi et al. 2022; Shanaida et al. 2021) in these residues that could be extracted with secondary processing, which is probably inexpedient (Scendi et al. 2022; Shanaida et al. 2021). On the other hand, in the perspective of the agronomic use of solid residues from MAP distillation, composts, produced from residues from sage and rosemary distillation, seemed to be a precious reservoir of beneficial microorganisms against soil-borne

diseases for plants (Zaccardelli et al. 2020). Although, the anti-pathogenic potential of certain essential oils of MAP is well documented in literature, further research is needed to clarify the specific effects of essential oils which remain in solid residues from MAP distillation on composts and soils (Greff et al. 2021). Furthermore, in the perspective of using the particular residues as amendments for cultivated soils, it is crucial to extend our limited knowledge regarding effects of the residues on soil microorganisms (Greff et al. 2021; Wang et al. 2021) and soil nutrient availability-immobilization, as well as on plant growth (Hassiotis 2010).

Although, there are studies referring to the use of solid residues from MAP distillation after mixing them with other materials in the production of composts and vermicomposts, there is lack of in-depth investigation into the agronomic value and effects of these products on soils and plants (Chrysargyris et al. 2023a; Zaccardelli et al. 2020, 2021). Moreover, there are no studies related to the effect of only solid residues from MAP distillation on soil properties, without previous processing or mixing them with other materials. Consequently, the issue of rational management of the initial or final solid residues from MAP distillation, by using them in agriculture, remains.

In Greece, the MAP which dominate in arable land are lavender (*Lavandula angustifolia* Mill.) and oregano (*Origanum vulgare* L.), followed by rosemary (*Rosmarinus officinalis* L.) and sage (*Salvia officinalis* L.) (C.A.P. 2020). In addition, Helichrysum (*Helichrysum italicum* (Roth) G. Don) is a traditional MAP, which includes 600 species worldwide and 25 species in Mediterranean region, with *Helichrysum italicum* spp. being the most common (Akaberi et al. 2019). Its cultivation has increased in recent years, due to the beneficial effects of its products on cosmetology and aesthetics. Furthermore, the cultivation of different varieties of industrial hemp (*Cannabis sativa* L.), with a tetrahydrocannabinol (THC) content lower than 0.2%, has been allowed in Greece, since 2016, according to the Official Government Gazette of the Hellenic Republic 929B/6-4-2016. As far as lavender, rosemary, sage and oregano are concerned, there are certain studies regarding their bioactive compounds and their reaction in composts, vermicomposts and biochar. However, knowledge regarding the role of the solid residues from MAP distillation as soil amendments and fertilizers is too limited (Nigam et al. 2018; Zaccardelli et al. 2021).

As it is obvious from the above, literature is too poor in respect to the suitability of solid residues from MAP distillation to be used as soil amendments. The specific residues could be used as soil amendments, organic fertilizers in particular, since they are plant residues and thus,

they contain essential nutrients for plant growth. In this perspective, we hypothesized that the solid residues from MAP distillation, applied to soils at common rates for plant residues, could provide soils with amounts of available nutrients adequate from plant growth, without causing any undesirable effect to soils and crops. Since, the investigation of this issue is too limited in literature, the particular issue is worthy to be thoroughly investigated.

The objectives of this work were a preliminary assessment of the effects of solid residues from distillation of the medicinal and aromatic plants of hemp, helichrysum, lavender, oregano, rosemary and sage on the chemical properties and fertility of an acid soil. Specifically, we tried to initially realize the fertilization capacity of the residues. Moreover, we tried to initially determine the optimal range of soil application rates of the specific residues for improving soil chemical properties and enhancing soil available macro- and micronutrients, avoiding at the same time degradation of soil quality (e.g. soil salinization) and crop damage (e.g. micronutrient phytotoxicities, N immobilization). Moreover, we chose to study a strongly to moderately acid soil to realize, apart from the preceding issues, the liming capacity of solid residues. In addition, the possibility of micronutrient phytotoxicities risks is common to such soils.

2 Materials and Methods

2.1 The Original Soil and the Solid Residues from the Distillation of Medicinal and Aromatic Plants

Adequate quantity of an acid soil was collected from Thessaloniki plain, in northern Greece. Then, the soil sample was air-dried, ground to pass a 10-mm sieve and used for the preparation of soil treatments.

The solid residues from MAP distillation, used in the current study, were collected from different industries of essential oils of northern Greece, right after the steam distillation process, during the period of July–September 2022. In particular, the solid residues were from plants of hemp, helichrysum, lavender, oregano, rosemary and sage. After collection, the residues were left for air-drying until constant weight, in a protected place. Then, separation of the flowers-leaves from the shoots was carried out for the air-dried residues of lavender, helichrysum and rosemary. This was done for the three species only, because their shoot biomass, which had been distilled, was considerable in respect to the flower-leaf biomass. The solid residues from the distillation of hemp were consisted only of leaves and flowers and as far as the solid residues from the distillation of the other

species are concerned, the shoot biomass was negligible in respect to the flower-leaf biomass. Since as it is known plant nutrient concentrations differ among plant tissues of species, the separation of the plant tissues (where it was possible) could reveal differences between the two kinds of residues, flowers-leaves and shoots, in respect to their performance as soil amendments. Consequently, the plant materials, which were tested as soil amendments in the study, were flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and shoot residues from the distillation of helichrysum, lavender and rosemary. Afterwards, all kinds of the air-dried solid residues were cut into small pieces and used for the soil treatments.

In addition, sub-samples of the residues were used for the determination of their total content of nutrients, in five replications. Specifically, organic carbon (C) and total nitrogen (N) were determined by an elementary analyzer and the macronutrients phosphorus (P) and potassium (K) and the micronutrients copper (Cu), zinc (Zn), iron (Fe), manganese (Mn) and boron (B) were measured after dry ashing at 500 °C, for at least 6 h and dissolution of the ash with 2 M hydrochloric acid (HCl) (Mills and Benton-Jones 1996). The analytical determinations of the elements were conducted by flame photometry for K, atomic absorption spectrometry for Cu, Zn, Fe and Mn, the molybdenum blue - ascorbic acid method for P (Kuo 1996) and the azomethine-H method for B (Keren 1996).

2.2 Soil Treatments with the Solid Residues from the Distillation of Medicinal and Aromatic Plants

In the beginning of October 2023, the solid residues were added to the air-dried soil at the rates of 0 (control), 1, 2, 4 and 8% (treatments), in three replications and the experimental design was the completely randomized (CR). Then, the soil treatments (Table 1), which were consisted of 300 g of soil each, were left for one month to homogenize with periodic wetting, mixing and air-drying. Deionized water was added in the soil treatments totally three times (1st, 8th and 15th day). Similar or even higher application rates to soil than those used in the current study of rosemary, sage and other MAP are also reported by other researchers (Chalkos et al. 2010; Chouliaras et al. 2007; Kadodiglou et al. 2014; Karamanoli et al.

2018). Although, the two higher application rates used in the current study, i.e. 4 and 8%, are not practical regarding the proper handling of the residues in field, they were chosen to ensure either the fertilization capacity of the residues or the possibility of causing phytotoxicity. Specifically, if no fertilization capacity of the residues would be evidenced at either the 1 or 2% application rate, then maybe this capacity would be evidenced at the 4 or even the 8% rate. On the other hand, it was expected that possible undesirable effects of soil application of residues to plants would be obvious at the 8% rate or from the lower rate of 4% and above.

Afterwards (the period of November-December 2023), the treatments were ground, passed through a 2-mm sieve and analyzed, in three replications, for pH in 1:2 w/v suspension with water, electrical conductivity (EC) in 1:5 w/v suspension with water (Rhoades 1996) and cation exchange capacity (CEC) by the method of Hexaamminecobalt(III) chloride $[\text{Co}(\text{NH}_4)_6\text{Cl}_3]$ (ISO 23470 2007). In addition, organic C was determined by the wet oxidation method (Walkley and Black 1934) and total N by the Kjeldahl method (Bremner 1996). Soil available nitrate-nitrogen ($\text{NO}_3\text{-N}$) and ammonium-nitrogen ($\text{NH}_4\text{-N}$) were extracted with 1 M potassium chloride (KCl) (Mulvaney 1996), P was determined by the Olsen method (Kuo 1996) and K was extracted with 1 M ammonium acetate ($\text{CH}_3\text{COONH}_4$), pH 7 (Thomas 1982). Soil available Cu, Zn, Fe and Mn were extracted with DTPA (Lindsay and Norvell 1978) and B was extracted with hot water (Keren 1996). For the analytical determinations of P, K, Cu, Zn, Fe, Mn and B, the methods reported in the previous subsection 2.1 were applied, whereas $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were determined by ultraviolet spectrometry and the sodium salicylate - sodium nitroprusside method, respectively (Mulvaney 1996).

2.3 Statistical Analysis

For each property of the solid residues from MAP distillation, one-way ANOVA was conducted. For each property of the soil treatments, within each kind of species residue (flowers-leaves or shoots), two-way ANOVA (species $\times$ rate) was conducted. In all cases, the protected LSD test was used for mean comparisons, at $p \leq 0.05$.

Table 1 Details concerning the soil treatments with the solid residues from the distillation of medicinal and aromatic plants

	Species					
	Hemp	Helichrysum	Lavender	Oregano	Rosemary	Sage
Residue	Flowers-leaves	Flowers-leaves	Flowers-leaves	Flowers-leaves	Flowers-leaves	Flowers-leaves
	-	Shoots	Shoots	-	Shoots	-
Rate (%)	0	1	2		4	8
Residue (g)/300 g of soil	0	3	6		12	24

3 Results

3.1 Properties of the Original Soil and the Composition of Solid Residues from the Distillation of Medicinal and Aromatic Plants

The soil was sandy-clay-loamy (SCL) in texture, with organic C and total N content of $0.84 \pm 0.01\%$ and $0.09 \pm 0.01\%$, respectively, whereas its pH was 5.3 ± 0.0 , EC was $0.07 \pm 0.01 \text{ dS m}^{-1}$ and CEC was $13.9 \pm 0.6 \text{ cmol}_c \text{ kg}^{-1}$. Furthermore, the concentrations of soil available macronutrients were: $\text{NO}_3\text{-N}$ $14.1 \pm 0.1 \text{ mg kg}^{-1}$, P $11.4 \pm 1.4 \text{ mg kg}^{-1}$ and K $203 \pm 6 \text{ mg kg}^{-1}$. Moreover, the concentrations of soil available micronutrients were Fe $30.7 \pm 2.3 \text{ mg kg}^{-1}$, Mn $237 \pm 9 \text{ mg kg}^{-1}$, Zn $0.21 \pm 0.01 \text{ mg kg}^{-1}$, Cu $1.36 \pm 0.04 \text{ mg kg}^{-1}$ and B $0.15 \pm 0.02 \text{ mg kg}^{-1}$. All the mean and standard deviation values of the properties are reported for control (0% application rate) in the respective figures and tables of the study.

Regarding the results of chemical composition of solid residues from MAP distillation, it seems that all residues contained considerable amounts of macro- and micronutrients, especially N-P-K (Table 2), and of organic C as well. Among the flower-leaf residues, those of hemp followed by lavender contained the significantly highest concentrations of macronutrients and in most cases of micronutrients (Table 2). Moreover, in almost all cases, the flower-leaf residues from the distillation of lavender, rosemary and helichrysum contained significantly higher concentrations of nutrients than their respective shoot residues (Table 2). As far as the C/N ratio of all residues is concerned, it ranged

from 15.8 to 74.5 (Table 2). It is worth noting that the C/N values of shoot residues were significantly higher than their respective flower-leaf residues (Table 2). In almost all cases, the C/N ratio of flower-leaf residues was lower or near to 25, i.e. the threshold value for soil N immobilization when organic materials are used as soil conditioners, whereas the C/N ratio of shoot residues ranged at levels well above the value of 25 (Table 2).

3.2 Chemical properties of the soil treated with the solid residues from the distillation of medicinal and aromatic plants

Soil pH significantly increased upon the addition of flower-leaf residues from the distillation of all MAP applied at the 4 and 8% rates. Especially for the hemp, rosemary and sage residues, pH increased upon their application at the 1% rate and above (Fig. 1a). It is worth noting that pH of soil treated with 4 or 8% residues from hemp distillation increased more than one unit. As far as soil pH within the same rate of residues is concerned, in all cases, treatments with the residues from hemp distillation had the significantly highest pH values (Fig. 1a). Regarding shoot residues from the distillation of the three species, soil pH significantly increased compared with control, upon the application rate of 8% in all cases, and additionally for the helichrysum and rosemary residues upon the 4% application rate (Fig. 1b).

The EC of all soil treatments with the residues significantly increased compared with control (Fig. 2a, b), and this increase followed the application rate increase of each residue. It is worth noting that a six- to tenfold increase of the

Table 2 Composition (mean $\pm$ SD) of the solid residues (flowers-leaves, shoots) from the distillation of medicinal and aromatic plants

Species (residues)	C (%)	N (%)	C/N	P (mg kg^{-1})	K (mg kg^{-1})
Hemp (flowers-leaves)	$41.8 \pm 0.7 \text{ d}^*$	$2.65 \pm 0.21 \text{ a}$	$15.8 \pm 1.2 \text{ e}$	$3338 \pm 206 \text{ a}$	$11,987 \pm 739 \text{ d}$
Helichrysum (flowers-leaves)	$47.3 \pm 0.5 \text{ b}$	$1.26 \pm 0.04 \text{ d}$	$37.5 \pm 0.8 \text{ c}$	$1062 \pm 94 \text{ de}$	$5839 \pm 120 \text{ e}$
Helichrysum (shoots)	$46.8 \pm 1.5 \text{ b}$	$0.97 \pm 0.03 \text{ e}$	$48.2 \pm 1.4 \text{ b}$	$560 \pm 9 \text{ f}$	$4413 \pm 207 \text{ f}$
Lavender (flowers-leaves)	$46.5 \pm 1.1 \text{ b}$	$1.90 \pm 0.15 \text{ bc}$	$24.6 \pm 2.4 \text{ d}$	$1911 \pm 95 \text{ b}$	$16,834 \pm 918 \text{ b}$
Lavender (shoots)	$44.1 \pm 1.4 \text{ c}$	$0.89 \pm 0.06 \text{ e}$	$49.8 \pm 3.1 \text{ b}$	$1076 \pm 22 \text{ cde}$	$22,033 \pm 1056 \text{ a}$
Oregano (flowers-leaves)	$42.2 \pm 0.5 \text{ cd}$	$1.79 \pm 0.13 \text{ bc}$	$23.6 \pm 1.4 \text{ d}$	$1983 \pm 79 \text{ b}$	$16,865 \pm 462 \text{ b}$
Rosemary (flowers-leaves)	$49.7 \pm 2.0 \text{ a}$	$1.95 \pm 0.19 \text{ b}$	$25.6 \pm 1.7 \text{ d}$	$1143 \pm 9 \text{ cd}$	$14,854 \pm 755 \text{ c}$
Rosemary (shoots)	$47.4 \pm 0.5 \text{ b}$	$0.64 \pm 0.07 \text{ f}$	$74.5 \pm 8.1 \text{ a}$	$976 \pm 85 \text{ e}$	$13,781 \pm 963 \text{ c}$
Sage (flowers-leaves)	$48.1 \pm 1.7 \text{ ab}$	$1.72 \pm 0.15 \text{ c}$	$28.0 \pm 1.4 \text{ d}$	$1181 \pm 21 \text{ c}$	$11,861 \pm 1478 \text{ d}$
Species (residues)	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	B (mg kg^{-1})
Hemp (flowers-leaves)	$14.2 \pm 1.5 \text{ a}$	$75.4 \pm 4.8 \text{ a}$	$327 \pm 44 \text{ d}$	$76.4 \pm 3.1 \text{ a}$	$74.0 \pm 1.6 \text{ a}$
Helichrysum (flowers-leaves)	$6.8 \pm 0.5 \text{ d}$	$14.2 \pm 0.9 \text{ f}$	$256 \pm 42 \text{ e}$	$45.0 \pm 1.5 \text{ c}$	$37.8 \pm 1.0 \text{ e}$
Helichrysum (shoots)	$3.7 \pm 0.5 \text{ e}$	$8.6 \pm 0.6 \text{ g}$	$189 \pm 28 \text{ f}$	$38.1 \pm 1.1 \text{ d}$	$33.7 \pm 2.0 \text{ f}$
Lavender (flowers-leaves)	$10.7 \pm 0.5 \text{ b}$	$19.8 \pm 1.5 \text{ e}$	$448 \pm 52 \text{ c}$	$57.5 \pm 0.9 \text{ b}$	$54.2 \pm 6.4 \text{ b}$
Lavender (shoots)	$3.0 \pm 0.3 \text{ e}$	$9.2 \pm 0.4 \text{ g}$	$204 \pm 22 \text{ f}$	$31.4 \pm 2.7 \text{ e}$	$35.0 \pm 1.0 \text{ ef}$
Oregano (flowers-leaves)	$9.0 \pm 0.5 \text{ c}$	$29.3 \pm 1.4 \text{ d}$	$1288 \pm 31 \text{ a}$	$79.0 \pm 2.8 \text{ a}$	$43.0 \pm 1.2 \text{ d}$
Rosemary (flowers-leaves)	$6.4 \pm 0.3 \text{ d}$	$33.8 \pm 1.6 \text{ c}$	$744 \pm 6 \text{ b}$	$39.9 \pm 3.6 \text{ d}$	$50.4 \pm 1.2 \text{ c}$
Rosemary (shoots)	$5.7 \pm 0.8 \text{ d}$	$22.2 \pm 2.9 \text{ e}$	$347 \pm 41 \text{ d}$	$15.7 \pm 1.8 \text{ f}$	$26.4 \pm 2.0 \text{ g}$
Sage (flowers-leaves)	$10.3 \pm 0.5 \text{ b}$	$40.3 \pm 1.7 \text{ b}$	$332 \pm 29 \text{ d}$	$79.2 \pm 2.6 \text{ a}$	$54.7 \pm 1.3 \text{ b}$

*Different letters indicate significant differences among means within the same column, using the protected LSD test, at $p \leq 0.05$

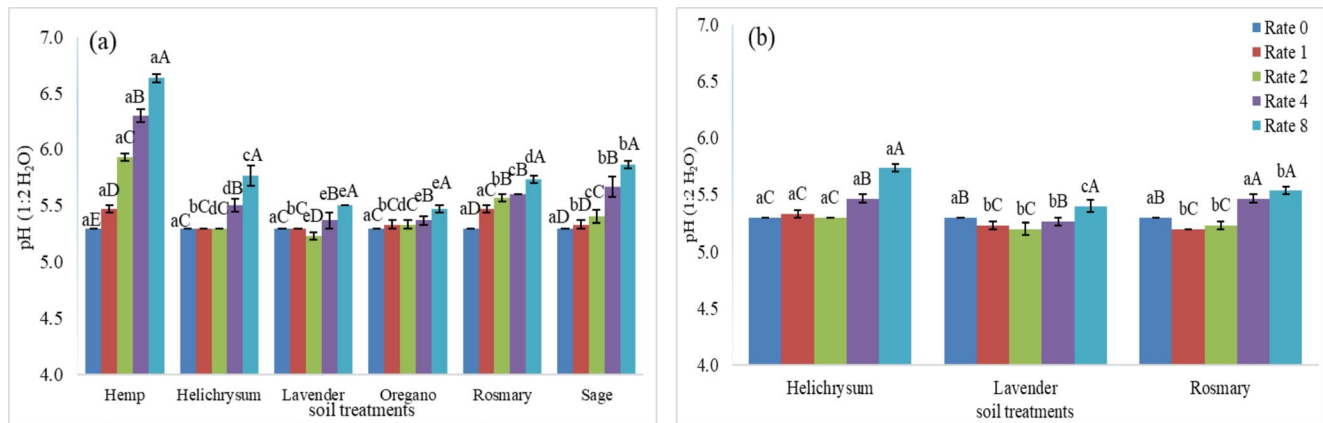


Fig. 1 pH (mean±SD) of the acid soil treatments, i.e. (a) soil with flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and (b) soil with shoot residues from the distillation of helichrysum, lavender and rosemary. Within each fig-

ure, different lower-case letters indicate significant differences among means, within the same rate, whereas different capital letters indicate significant differences among means, within the same residue, using the protected LSD test, at $p \leq 0.05$

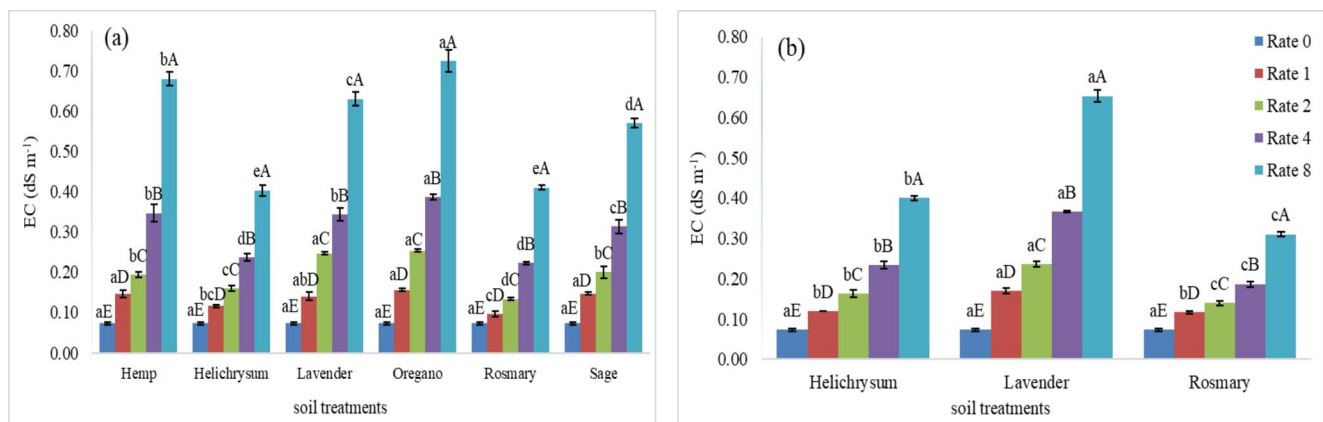


Fig. 2 EC (mean±SD) of the acid soil treatments, i.e. (a) soil with flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and (b) soil with shoot residues from the distillation of helichrysum, lavender and rosemary. Within each fig-

ure, different lower-case letters indicate significant differences among means, within the same rate, whereas different capital letters indicate significant differences among means, within the same residue, using the protected LSD test, at $p \leq 0.05$

initial EC was observed upon the 8% application of flower-leaf residues. In addition, within each application rate, the treatments with the aforementioned residues from the distillation of hemp, lavender and oregano showed the significantly highest EC values in almost all cases (Fig. 2a). As far as the treatments with the shoot residues are concerned, the significantly highest EC values, within each addition rate, were observed in the soil treatments with the residues from lavender distillation (Fig. 2b).

The CEC of almost all soil treatments, with the 4 and 8% application rates of flower-leaf residues, apart from helichrysum, and with the 8% rate of shoot residues, apart from rosemary, significantly increased compared with control (Fig. 3a, b). However, in all cases, the CEC remained moderate as that of the original soil (Fig. 3a, b).

Soil organic C significantly increased upon the addition of all kinds of residues of all species at the 2, 4 and 8%

rates in comparison with control (Fig. 4a, b). Similar results were obtained for the total N of treatments with the flower-leaf residues from the distillation of hemp (at the 2% rate and above), lavender, oregano and sage (at the 1% rate and above), rosemary (at the 4 and 8% rates) and helichrysum (at the 8% rate) (Fig. 5a). As far as the treatments with shoot residues are concerned, significant increases were obtained for the treatments with helichrysum, whereas for the treatments with lavender and rosemary the results were rather inconclusive (Fig. 5b).

Following the increases of organic C and total N, also the C/N ratio of most soil treatments with the distillation residues significantly increased in comparison with control (Fig. 6a, b). The C/N values of soil treatments with the flower-leaf residues of 2, 4 and 8% helichrysum, 8% lavender and 8% rosemary (Fig. 6a) and with the shoot residues

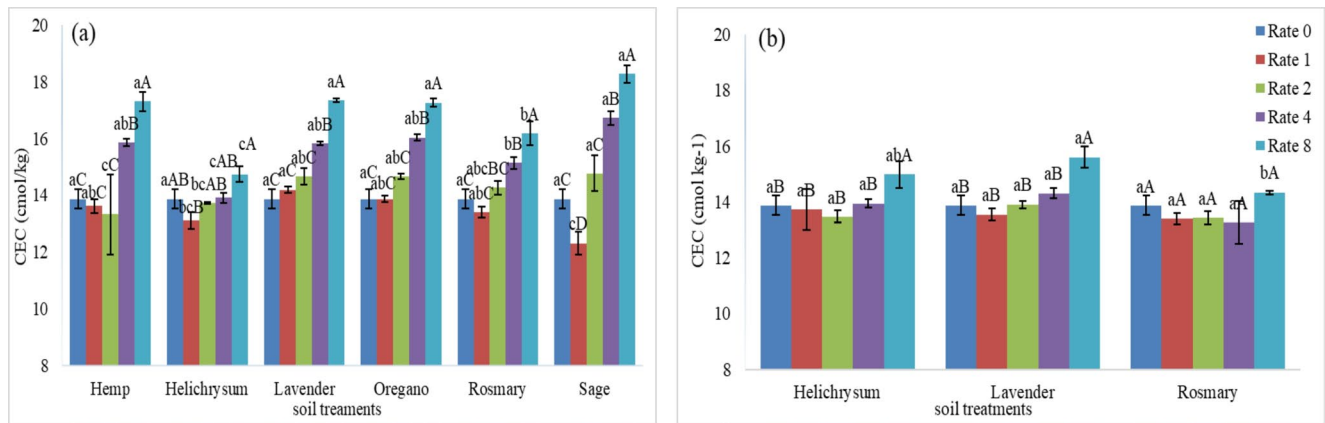


Fig. 3 CEC (mean $\pm$ SD) of the acid soil treatments, i.e. (a) soil with flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and (b) soil with shoot residues from the distillation of helichrysum, lavender and rosemary. Within each fig-

ure, different lower-case letters indicate significant differences among means, within the same rate, whereas different capital letters indicate significant differences among means, within the same residue, using the protected LSD test, at $p \leq 0.05$

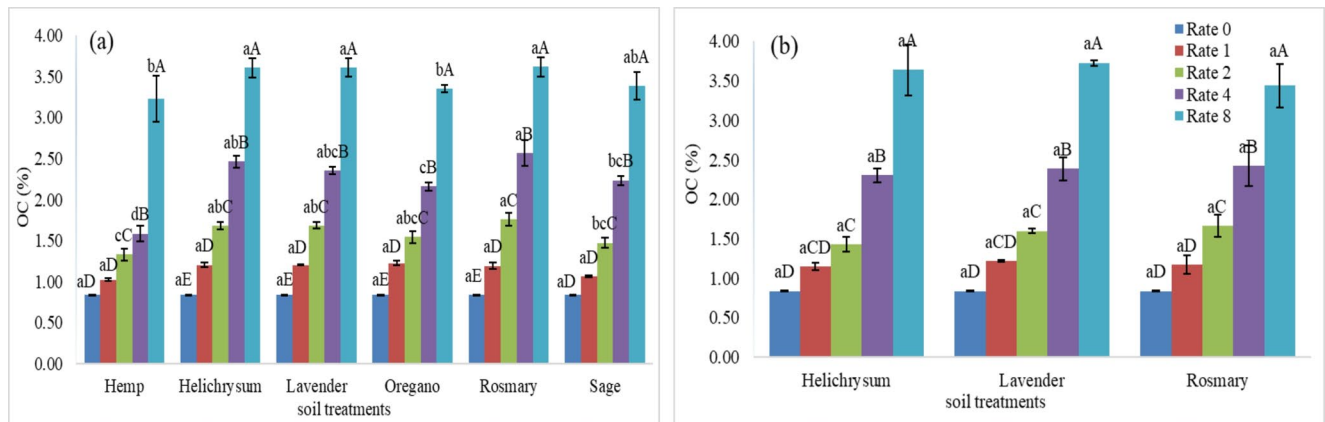


Fig. 4 Organic C (mean $\pm$ SD) of the acid soil treatments, i.e. (a) soil with flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and (b) soil with shoot residues from the distillation of helichrysum, lavender and rosemary. Within

each figure, different lower-case letters indicate significant differences among means, within the same rate, whereas different capital letters indicate significant differences among means, within the same residue, using the protected LSD test, at $p \leq 0.05$

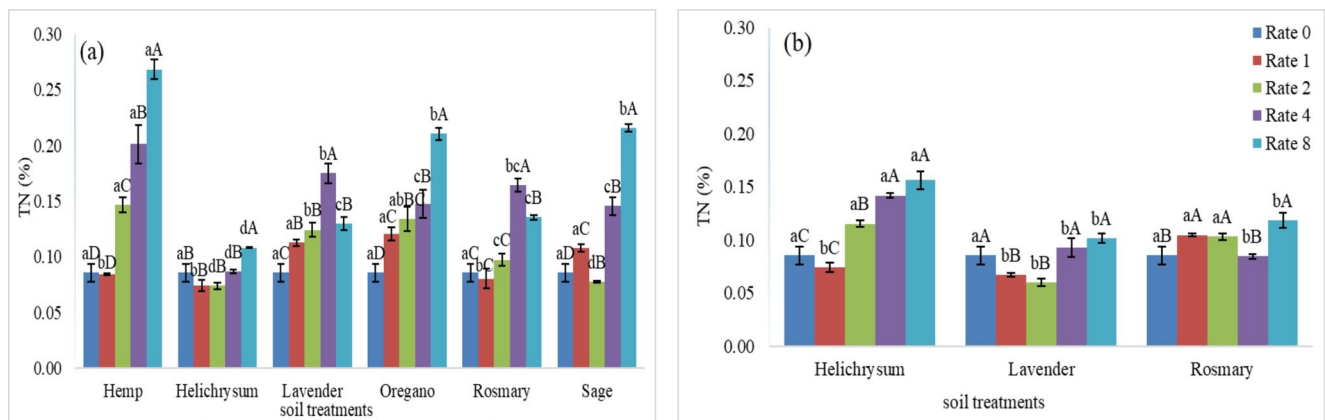


Fig. 5 Total N (mean $\pm$ SD) of the acid soil treatments, i.e. (a) soil with flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and (b) soil with shoot residues from the distillation of helichrysum, lavender and rosemary. Within each fig-

ure, different lower-case letters indicate significant differences among means, within the same rate, whereas different capital letters indicate significant differences among means, within the same residue, using the protected LSD test, at $p \leq 0.05$

of 8% helichrysum, 2, 4 and 8% lavender and 4 and 8% rosemary (Fig. 6b), were two-three times that of control.

3.3 Fertility of the soil treated with the solid residues from the distillation of medicinal and aromatic plants

In the soil treatments with flower-leaf residues from the distillation of helichrysum, rosemary and sage, only the 8% application rate caused a significant increase of the soil available $\text{NO}_3\text{-N}$ concentrations, whereas in the cases of hemp, lavender and oregano, significant increases were observed from the 2% rate and above and followed the application rate increase of each residue. Contrary to the above, no significant differences were observed between all soil treatments with the 1% application rate of residues and control (Table 3). Similar results were obtained for the soil treatments with shoot residues (Table 4). As far as the concentrations of soil available $\text{NH}_4\text{-N}$ is concerned, a decreasing trend, significant in most cases, was evidenced with the increase of application rate of all kinds of residues compared with control, except for the flower-leaf residues from hemp distillation where the opposite trend was observed (Tables 3 and 4).

Almost similar trends to those of soil available $\text{NO}_3\text{-N}$ were observed for soil available P upon addition of the distillation residues. Specifically, in the soil treatments with flower-leaf residues from the distillation of helichrysum and rosemary, the 4 and 8% addition rates caused a significant increase in P concentrations, whereas in the cases of hemp, lavender, oregano and sage significant increases were observed from the 1% rate and afterwards (Table 3). Moreover, it is worth noting that in the soil treatments with all application rates of the residues of hemp soil available P concentrations were high to very high (Table 3). As far as

the treatments with shoot residues from the distillation of the three species are concerned, soil available P concentrations significantly increased compared with control, upon the application rate of 8% in all cases, and additionally for the lavender and rosemary residues upon the application rates of 2 and 4% (Table 4).

Upon the application of all kinds of residues, soil available K significantly increased compared with control, with the increase following the application rate increase in all cases (Tables 3 and 4). Within the same application rate, the soil treatments with residues from lavender distillation had the highest K concentrations (Tables 3 and 4).

As far as the micronutrients are concerned, soil available B significantly increased in all treatments with all kinds of residues applied at the 1% rate and above in comparison with control, except for rosemary residues (Tables 5 and 6). It is worth noting that B concentrations increased two-four times, upon the 1% addition of flower-leaf residues from MAP distillation, and six-12 times upon the 8% addition of the same residues, apart from those of rosemary and sage. Moreover, the 4% addition of flower-leaf residues from the distillation of hemp and lavender resulted in a sevenfold increase in B concentrations (Table 5). Furthermore, B concentrations increased five-seven times upon the 8% addition of shoot residues from the distillation of helichrysum and lavender (Table 6).

Regarding the available metal micronutrients, as for B similar results were obtained for Zn in the treatments with flower-leaf residues from the distillation of all MAP (Table 5), whereas in the treatments with shoot residues Zn also significantly increased compared with control, but at different application rates for each species (Table 6). It is worth noting that Zn concentrations increased seven and nine times in the soil treatments with the 8% addition of flower-leaf residues from the distillation of sage and hemp, respectively. As for

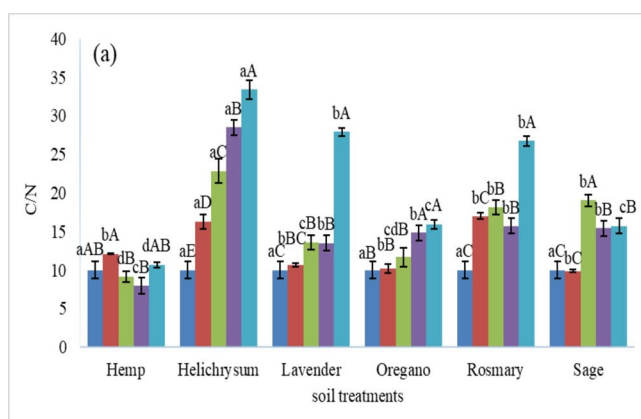
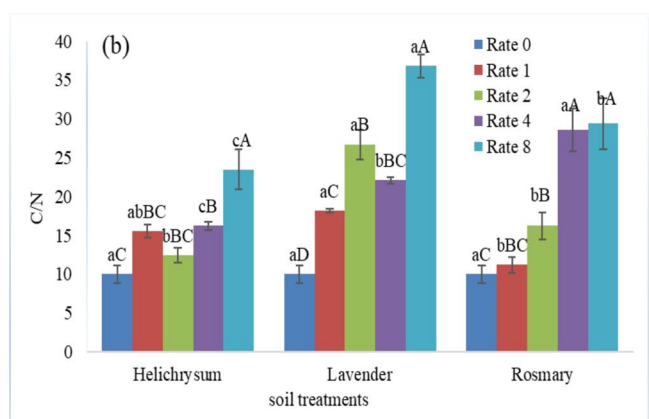


Fig. 6 The C/N ratio (mean $\pm$ SD) of the acid soil treatments. i.e. (a) soil with flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage and (b) soil with shoot residues from the distillation of helichrysum, lavender and rosemary.



Within each figure, different lower-case letters indicate significant differences among means, within the same rate, whereas different capital letters indicate significant differences among means, within the same residue, using the protected LSD test, at $p \leq 0.05$

Table 3 Concentrations of available macronutrients (mean $\pm$ SD) of the acid soil treated with the flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, Rosemary and Sage

Rate (%)	Species					
	Hemp	Helichrysum	Lavender	Oregano	Rosemary	Sage
	NO ₃ -N (mg kg ⁻¹)					
0	14.1 $\pm$ 0.1 aD*	14.1 $\pm$ 0.1 aB	14.1 $\pm$ 0.1 aD	14.1 $\pm$ 0.1 aD	14.1 $\pm$ 0.1 aBC	14.1 $\pm$ 0.1 aB
1	27.3 $\pm$ 1.7 aCD	22.1 $\pm$ 1.9 abB	20.7 $\pm$ 2.5 abD	29.0 $\pm$ 5.3 aCD	8.0 $\pm$ 1.2 bC	16.6 $\pm$ 0.7 abB
2	35.7 $\pm$ 2.8 aC	27.6 $\pm$ 2.7 aB	38.1 $\pm$ 4.4 aC	34.2 $\pm$ 3.6 aC	6.8 $\pm$ 1.1 bC	28.9 $\pm$ 1.8 aB
4	66.2 $\pm$ 6.5 aB	26.4 $\pm$ 3.0 bB	61.8 $\pm$ 3.7 aB	71.7 $\pm$ 4.4 aB	27.8 $\pm$ 0.9 bB	21.4 $\pm$ 1.5 bB
8	134 $\pm$ 13.8 cA	56.3 $\pm$ 1.2 dA	269 $\pm$ 15 bA	302 $\pm$ 47 aA	59.6 $\pm$ 1.8 dA	60.7 $\pm$ 5.9 dA
	<i>p</i> F-test					
Rate	<0.001					
Residue	<0.001					
Interaction	<0.001					
	NH ₄ -N (mg kg ⁻¹)					
0	33.3 $\pm$ 0.3 aC	33.3 $\pm$ 0.3 aA	33.3 $\pm$ 0.3 aA	33.3 $\pm$ 0.3 aA	33.3 $\pm$ 0.3 aA	33.3 $\pm$ 0.3 aA
1	39.2 $\pm$ 1.0 aB	25.4 $\pm$ 3.7 cB	23.9 $\pm$ 3.6 cB	32.9 $\pm$ 3.3 bA	18.0 $\pm$ 2.9 dB	32.4 $\pm$ 2.7 bA
2	38.4 $\pm$ 3.3 aB	19.1 $\pm$ 1.6 dC	24.9 $\pm$ 0.2 cB	26.6 $\pm$ 1.8 bcB	16.3 $\pm$ 0.7 dBC	29.2 $\pm$ 1.5 bB
4	40.2 $\pm$ 5.7 aB	16.5 $\pm$ 0.4 bC	15.2 $\pm$ 0.4 bC	15.7 $\pm$ 0.9 bC	14.1 $\pm$ 0.7 bCD	15.4 $\pm$ 1.0 bC
8	54.5 $\pm$ 0.2 aA	12.8 $\pm$ 0.7 bD	12.0 $\pm$ 0.4 bD	8.8 $\pm$ 0.3 cD	11.6 $\pm$ 0.6 bcD	11.3 $\pm$ 0.9 bcD
	<i>p</i> F-test					
Rate	<0.001					
Residue	<0.001					
Interaction	<0.001					
	P (mg kg ⁻¹)					
0	11.4 $\pm$ 1.4 aE	11.4 $\pm$ 1.4 aB	11.4 $\pm$ 1.4 aD	11.4 $\pm$ 1.4 aD	11.4 $\pm$ 1.4 aC	11.4 $\pm$ 1.4 aC
1	22.6 $\pm$ 1.3 aD	14.9 $\pm$ 0.9 bcAB	18.6 $\pm$ 3.4 abC	15.9 $\pm$ 1.3 bC	11.2 $\pm$ 0.3 cC	15.8 $\pm$ 1.7 bB
2	33.2 $\pm$ 2.3 aC	14.1 $\pm$ 1.4 dAB	22.8 $\pm$ 1.3 bBC	19.1 $\pm$ 1.4 bcC	15.4 $\pm$ 0.8 cdC	17.0 $\pm$ 2.9 cdB
4	53.9 $\pm$ 6.2 aB	16.2 $\pm$ 1.7 eA	25.2 $\pm$ 0.7 bcB	29.2 $\pm$ 2.2 bB	21.0 $\pm$ 0.9 cdB	19.2 $\pm$ 2.5 deB
8	92.1 $\pm$ 7.3 aA	18.0 $\pm$ 2.3 eA	34.3 $\pm$ 4.5 cA	46.2 $\pm$ 4.5 bA	26.6 $\pm$ 3.0 dA	26.6 $\pm$ 0.6 dA
	<i>p</i> F-test					
Rate	<0.001					
Residue	<0.001					
Interaction	<0.001					
	K (mg kg ⁻¹)					
0	203 $\pm$ 6 aE	203 $\pm$ 6 aE	203 $\pm$ 6 aE	203 $\pm$ 6 aE	203 $\pm$ 6 aE	203 $\pm$ 6 aE
1	327 $\pm$ 6 bcD	263 $\pm$ 15 dD	360 $\pm$ 10 aD	360 $\pm$ 36 aD	337 $\pm$ 12 abD	297 $\pm$ 6 cD
2	400 $\pm$ 10 cC	323 $\pm$ 40 dC	503 $\pm$ 21 aC	440 $\pm$ 20 bC	433 $\pm$ 15 bC	370 $\pm$ 17 cC
4	610 $\pm$ 26 bB	387 $\pm$ 21 dB	700 $\pm$ 20 aB	670 $\pm$ 30 aB	597 $\pm$ 6 bB	480 $\pm$ 17 cB
8	957 $\pm$ 35 cA	497 $\pm$ 35 eA	1150 $\pm$ 10 aA	1080 $\pm$ 20 bA	937 $\pm$ 21 cA	707 $\pm$ 35 dA
	<i>p</i> F-test					
Rate	<0.001					
Residue	<0.001					
Interaction	<0.001					

*Different lower-case letters indicate significant differences among means within the same row, whereas different capital letters indicate significant differences among means within the same column, using the protected LSD test, at $p \leq 0.05$

Zn, similar results were obtained for Mn in the treatments with flower-leaf residues from the distillation of almost all MAP, except for hemp (Table 5), whereas in the treatments with shoot residues Mn also significantly increased compared with control, but at different application rates for each species. On the contrary to Zn and B, it is worth noting for Mn, that in all cases the observed Mn increases in the soil treatments with the residues did not exceed around the one and a half times the initial Mn concentration of soil.

Soil available Cu concentrations were not affected by treatment, or the results were rather inconclusive, except for the soil treatments with flower-leaf residues from hemp distillation (Table 5) and with the shoot residues from helichrysum distillation (Table 6), where Cu concentrations significantly increased from the 2% and 4% application rates and afterwards, respectively. Similarly, Fe concentrations were not affected by treatment, or the results were rather inconclusive except for the soil treatments with flower-leaf

Table 4 Concentrations of available macronutrients (mean $\pm$ SD) of the acid soil treated with the shoot residues from the distillation of helichrysum, lavender and Rosemary

Rate (%)	Species					
	Helichrysum	Lavender	Rosemary	Helichrysum	Lavender	Rosemary
	NO ₃ -N (mg kg ⁻¹)			NH ₄ -N (mg kg ⁻¹)		
0	14.1 $\pm$ 0.1 aB*	14.1 $\pm$ 0.1 aD	14.1 $\pm$ 0.1 aB	33.3 $\pm$ 0.3 aA	33.3 $\pm$ 0.3 aA	33.3 $\pm$ 0.3 aA
1	17.8 $\pm$ 2.1 aB	28.3 $\pm$ 2.8 aD	21.8 $\pm$ 2.7 aAB	27.5 $\pm$ 0.7 abB	26.3 $\pm$ 1.6 bB	29.2 $\pm$ 1.3 aB
2	21.0 $\pm$ 1.8 bB	55.5 $\pm$ 4.8 aC	24.1 $\pm$ 0.9 bAB	19.9 $\pm$ 0.1 bC	22.0 $\pm$ 1.2 aC	22.9 $\pm$ 3.8 aC
4	26.9 $\pm$ 2.1 bB	106 $\pm$ 3.9 aB	14.2 $\pm$ 0.9 bB	17.7 $\pm$ 0.4 aD	14.9 $\pm$ 0.3 bD	17.8 $\pm$ 1.2 aD
8	51.0 $\pm$ 3.8 bA	213 $\pm$ 35 aA	33.9 $\pm$ 3.7 cA	13.7 $\pm$ 1.0 aE	11.3 $\pm$ 0.6 bE	15.4 $\pm$ 1.1 aE
	<i>p</i> F-test			<i>p</i> F-test		
Rate	<0.001			<0.001		
Residue	<0.001			<0.001		
Interaction	<0.001			0.028		
	P (mg kg ⁻¹)			K (mg kg ⁻¹)		
0	11.4 $\pm$ 1.4 aB	11.4 $\pm$ 1.4 aE	11.4 $\pm$ 1.4 aD	203 $\pm$ 6 aE	203 $\pm$ 6 aE	203 $\pm$ 6 aE
1	12.7 $\pm$ 1.0 bB	15.1 $\pm$ 1.4 abD	16.3 $\pm$ 2.9 aC	247 $\pm$ 12 cD	393 $\pm$ 12 aD	327 $\pm$ 6 bD
2	13.5 $\pm$ 1.2 bAB	19.0 $\pm$ 2.1 aC	18.0 $\pm$ 0.9 aBC	280 $\pm$ 10 cC	527 $\pm$ 25 aC	427 $\pm$ 12 bC
4	13.9 $\pm$ 1.2 cAB	24.5 $\pm$ 0.7 aB	20.3 $\pm$ 2.0 bB	323 $\pm$ 6 cB	810 $\pm$ 36 aB	567 $\pm$ 15 bB
8	15.8 $\pm$ 0.7 cA	28.7 $\pm$ 0.3 aA	25.1 $\pm$ 3.0 bA	407 $\pm$ 12 cA	1357 $\pm$ 51 aA	887 $\pm$ 21 bA
	<i>p</i> F-test			<i>p</i> F-test		
Rate	<0.001			<0.001		
Residue	<0.001			<0.001		
Interaction	<0.001			<0.001		

*Different lower-case letters indicate significant differences among means within the same row, whereas different capital letters indicate significant differences among means within the same column, using the protected LSD test, at $p \leq 0.05$

residues from the distillation of lavender and oregano, where Fe concentrations significantly increased from the 1% and 2% application rates and afterwards, respectively (Table 5). Regarding shoot residues from the distillation of lavender and rosemary, Fe concentrations significantly increased upon their addition at the 2% rate and above in comparison with control (Table 6).

4 Discussion

The soil was inorganic, strongly to moderately acidic in reaction and had low salinity and moderate CEC (Brady and Weil 2008). Furthermore, it contained adequate NO₃-N (Dahnke and Johnson 1990), low to marginally sufficient P according to Thomas and Peaslee (1973) (P lowest sufficiency level 10 mg kg⁻¹) and sufficient to high K according to Haby et al. (1990) (K lowest sufficiency level 110 mg kg⁻¹). Moreover, according to Sims and Johnson (1991) (sufficiency levels in mg kg⁻¹ 0.1–2.1 for B, 0.1–2.5 for Cu, 0.2–2.2 for Zn, 2.5–5.5 for Fe and 1–5 for Mn), the concentrations of soil available micronutrients B and Zn were low, that of Cu was within the sufficiency range and Fe and Mn were high. Especially for Mn, its concentration was at levels that could be considered as toxic. According to Fageria (2001), toxic concentrations of DTPA extractable Mn greatly varied among crops and ranged between 40 and 336

mg kg⁻¹, causing a 10% decrease in dry matter yield of five crops grown in an oxisol.

In general, nutrient content of the solid residues from MAP distillation varied greatly, depending on the species and kind of residues. Furthermore, it is reported that the initial nutrient composition of MAP is not affected by steam distillation (Lesage-Meessen et al. 2015). In agreement with the findings of the present study, considerable concentrations of macro- and micronutrients are reported for solid residues from distillation of other MAP than those reported herein [Japanese mint (*Mentha arvensis* L.) 1.35–1.80% N, 0.45–0.60% P, 2.00–2.25% K; Cypriot Oregano (*Origanum dubium* Boiss) and Cyprus ironwort (*Sideritis cypria* Post.) 53.8 and 53.8% C, 1.05 and 1.26% N, 13.46 and 14.6 g kg⁻¹ K, 2.83 and 1.65 g kg⁻¹ P, respectively] (Chand et al. 2004; Chrysargyris et al. 2023b) and similar chemical composition is reported for distilled straws of lavender (48.1% C and 1.3% N) (Lesage-Meessen et al. 2015). On the other hand, solid residues of lavender and hemp, which were used for biogas production, had macro- and micronutrients concentrations lower than those of this study (Kontodimos et al. 2025). Specifically, Kontodimos et al. (2025) reported 47.2 and 46.5% C, 1.2 and 1.3, % N, 2.12 and 1.09% K, 141 and 108 mg kg⁻¹ Fe, 6.9 and 14.5 mg kg⁻¹ Cu, and 10.2 and 32.3 mg kg⁻¹ Zn for solid residues from lavender and hemp distillation, respectively.

Table 5 Concentrations of available micronutrients (mean±SD) of the acid soil treated with the flower-leaf residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and Sage

Rate (%)	Species	Hemp	Helichrysum	Lavender	Oregano	Rosemary	Sage
B (mg kg ⁻¹)							
0		0.15±0.02 aD*	0.15±0.02 aD	0.15±0.02 aD	0.15±0.02 aD	0.15±0.02 aC	0.15±0.02 aD
1		0.52±0.01 aC	0.41±0.01 bC	0.61±0.04 aC	0.39±0.02 bC	0.37±0.02 bA	0.41±0.01 bBC
2		0.61±0.06 aC	0.48±0.03 bC	0.61±0.06 aC	0.45±0.02 bC	0.21±0.01 cBC	0.50±0.03 bAB
4		1.02±0.03 aB	0.58±0.02 bB	0.98±0.03 aB	0.63±0.03 bB	0.20±0.01 dC	0.36±0.02 cC
8		1.82±0.24 aA	0.88±0.12 cA	1.66±0.13 bA	0.97±0.02 cA	0.30±0.03 eAB	0.55±0.08 dA
<i>p</i> F-test							
Rate		<0.001					
Residue		<0.001					
Interaction		<0.001					
Cu (mg kg ⁻¹)							
0		1.36±0.04 aD	1.36±0.04 aB	1.36±0.04 aB	1.36±0.04 aA	1.36±0.04 aC	1.36±0.04 aB
1		1.48±0.14 aCD	1.32±0.06 beB	1.19±0.02 cC	1.40±0.03 abA	1.46±0.08 abBC	1.35±0.07 abB
2		1.52±0.16 abBC	1.43±0.07 beB	1.53±0.16 abA	1.43±0.11 bcA	1.66±0.18 aA	1.36±0.02 cB
4		1.65±0.03 aB	1.63±0.08 aA	1.28±0.02 cBC	1.44±0.08 bA	1.53±0.07 abAB	1.45±0.13 bB
8		1.94±0.21 aA	1.47±0.13 cB	1.26±0.12 dBC	1.43±0.13 cA	1.40±0.03 cdBC	1.64±0.09 bA
<i>p</i> F-test							
Rate		<0.001					
Residue		<0.001					
Interaction		<0.001					
Zn (mg kg ⁻¹)							
0		0.21±0.01 aD	0.21±0.01 aD	0.21±0.01 aD	0.21±0.01 aD	0.21±0.01 aE	0.21±0.01 aE
1		0.56±0.03 aC	0.26±0.05 cCD	0.35±0.06 bcC	0.36±0.02 bC	0.33±0.03 bcD	0.36±0.01 bD
2		0.63±0.04 aC	0.35±0.05 cC	0.43±0.06 bcBC	0.44±0.06 bcC	0.47±0.05 bC	0.50±0.03 bC
4		1.00±0.06 aB	0.47±0.06 dB	0.45±0.03 dB	0.54±0.03 cdB	0.59±0.02 cB	0.86±0.11 bB
8		1.86±0.20 aA	0.63±0.06 dA	0.64±0.06 dA	0.86±0.08 cA	0.80±0.04 cA	1.48±0.10 bA
<i>p</i> F-test							
Rate		<0.001					
Residue		<0.001					
Interaction		<0.001					
Fe (mg kg ⁻¹)							
0		30.7±2.3 aA	30.7±2.3 aA	30.7±2.3 aC	30.7±2.3 aB	30.7±2.3 aC	30.7±2.3 aB
1		27.9±1.3 dAB	29.4±2.1 cdA	33.6±4.7 bcBC	42.1±7.7 aA	35.9±3.6 bABC	36.1±1.3 bA
2		25.0±1.6 bB	29.4±0.8 bA	42.5±6.1 aA	42.3±2.4 aA	38.0±2.5 aA	37.6±1.6 aA
4		24.2±2.3 cB	30.4±2.2 bA	37.1±2.6 aB	39.2±1.3 aA	36.0±1.6 aAB	35.9±2.7 aAB
8		28.4±5.6 bAB	21.8±2.5 cB	38.5±2.7 aAB	39.0±7.2 aA	32.0±1.4 bBC	33.0±2.0 bAB
<i>p</i> F-test							
Rate		<0.001					

Table 5 (continued)

Rate (%)	Species	Hemp	Helichrysum	Lavender	Oregano	Rosemary	Sage
Residue							
Interaction							
0	Mn (mg kg ⁻¹)	237 ± 9 aC	237 ± 9 aD	237 ± 9 aC	237 ± 9 aD	237 ± 9 aD	237 ± 9 aD
1		276 ± 24 bB	274 ± 29 bC	291 ± 12 bB	331 ± 32 aC	331 ± 32 aC	263 ± 16 bD
2		278 ± 29 cdB	307 ± 4 bcBC	325 ± 39 bAB	383 ± 22 aAB	383 ± 22 aAB	306 ± 8 bcC
4		385 ± 31 aA	324 ± 25 cdB	305 ± 20 dAB	366 ± 22 abBC	366 ± 22 abBC	348 ± 19 bcB
8		400 ± 26 abA	370 ± 24 bcA	336 ± 36 cA	407 ± 28 aA	407 ± 28 aA	394 ± 24 abA
Rate	p F-test						
Residue		<0.001					
Interaction		<0.001					

*Different lower-case letters indicate significant differences among means within the same row, whereas different capital letters indicate significant differences among means within the same column, using the protected LSD test, at $p \leq 0.05$

As far as the C/N ratio is concerned, similar results are reported by Zaccardelli et al. (2021) and Lesage-Meessen et al. (2015) for solid residues from rosemary distillation (C/N 33–43) and lavender distillation (C/N 37), respectively. It is widely accepted that the C/N value of various organic substances (e.g., plant residues) determines the feasibility of using these substances as soil amendments; the C/N value being depended on the mineralization rate of applied organic N (Sloot et al. Please, delete ", ".2022). Furthermore, values of C/N ratio well above 25, could lead to N immobilization after the incorporation of organic materials to soil (Brady and Weil 2008; Sloot et al. 2022); however, this is also depended on the composition of organic materials, e.g. content of lignin and polyphenols (Kaleem Abbasi et al. 2015; Vahdat et al. 2011), as well as on soil available N (Yadav et al. 2019).

Since the solid residues of MAP distillation differ in their composition (Tao et al. 2021), as it is also shown in Table 2 of the current study, the same rates of residues applied to the acid soil affected differently the various soil chemical properties and fertility indices, depending on the residues' origin and composition.

Beginning with the soil chemical properties, variable results are reported in literature regarding the effect of plant residues addition on soil pH, depending mainly on the initial pH of the studied soil. For alkaline soils, Kadodiglou et al. (2014) reported that soil pH was not affected by the incorporation of plant tissues of spearmint (*Mentha spicata* L.) and sage (*Salvia fruticosa* Mill.) and remained alkaline. The same is reported by Chouliaras et al. (2007) for the alkaline pH of a soil after the addition of compost constituted by organic matter and basil (*Ocimum basilicum* L.). However, for acid soils like the one used in the current study, Zhou et al. (2023) reported that compost produced by Chinese medicinal herbal residues raised soil pH from 4.3 to 5.2–7.2, depending on the addition rate. Moreover, Nigam et al. (2018) reported that biochar produced from distillation biomass of menthol mint (*Mentha arvensis* L.) can be used in strongly acid soils as a liming agent due to its aromatic structure, de-protonated surface functional groups and high concentrations of base cations of biochar. The preceding explanation of Nigam et al. (2018) could also justify the observed liming effect of the solid residues, from the specific MAP distillation used in the current study, on the acid soil, especially at the 4 and 8% application rates (Fig. 1a, b). Furthermore, the increase of soil pH by more than one unit, upon the 4 and 8% addition of residues from hemp distillation, changed the characterization of soil to slightly acid from strongly to moderately acid (Brady and Weil 2008). Consequently, it seems that acid soils, which commonly have lower buffering capacity than alkaline soils (Brady and Weil 2008), could benefit from the addition

Table 6 Concentrations of available micronutrients (mean $\pm$ SD) of the acid soil treated with the shoot residues from the distillation of helichrysum, lavender and Rosemary

Rate (%)		Species					
		Helichrysum		Lavender		Rosemary	
		B (mg kg ⁻¹)					
0		0.15±0.02 aC*		0.15±0.02 aD		0.15±0.02 aC	
1		0.39±0.05 bB		0.58±0.07 aC		0.22±0.01 cBC	
2		0.40±0.06 bB		0.66±0.11 aBC		0.23±0.02 cABC	
4		0.50±0.01 bB		0.77±0.07 aB		0.29±0.01 cAB	
8		0.76±0.04 bA		1.08±0.20 aA		0.34±0.02 cA	
		<i>p</i> F-test					
Rate		<0.001					
Residue		<0.001					
Interaction		0.001					
		Species					
		Helichrysum	Lavender	Rosemary	Helichrysum	Lavender	Rosemary
		Cu (mg kg ⁻¹)			Zn (mg kg ⁻¹)		
0		1.36±0.04 aC	1.36±0.04 aA	1.36±0.04 aA	0.21±0.01 aD	0.21±0.01 aC	0.21±0.01 aE
1		1.39±0.15 abBC	1.26±0.06 bA	1.60±0.09 aA	0.27±0.04 bD	0.28±0.04 abC	0.35±0.04 aD
2		1.53±0.19 aBC	1.37±0.08 bA	1.59±0.17 aA	0.37±0.07 bC	0.26±0.02 cC	0.45±0.04 aC
4		1.63±0.28 aAB	1.34±0.08 bA	1.49±0.08 abA	0.48±0.08 bB	0.39±0.04 cB	0.58±0.04 aB
8		1.83±0.31 aA	1.37±0.10 bA	1.60±0.14 abA	0.69±0.09 bA	0.58±0.06 cA	0.92±0.07 aA
		<i>p</i> F-test			<i>p</i> F-test		
Rate		0.021			<0.001		
Residue		<0.001			<0.001		
Interaction		NS [#]			<0.001		
		Fe (mg kg ⁻¹)			Mn (mg kg ⁻¹)		
0		30.7±2.3 aBC	30.7±2.3 aD	30.7±2.3 aC	237±9 aC	237±9 aC	237±9 aC
1		33.4±1.3 aABC	34.3±3.8 aCD	34.8±3.1 aBC	271±27 aBC	265±17 aC	297±17 aB
2		35.8±2.2 bA	35.8±1.6 bBC	41.2±2.5 aA	316±54 abB	269±14 bBC	360±14 aA
4		34.9±0.9 bAB	39.0±1.7 abB	39.5±1.6 aA	299±14 aB	316±37 aB	319±10 aAB
8		29.4±5.4 cC	47.2±3.8 aA	39.1±2.8 aAB	365±37 abA	401±39 aA	352±53 bA
		<i>p</i> F-test			<i>p</i> F-test		
Rate		<0.001			<0.001		
Residue		<0.001			NS		
Interaction		<0.001			0.034		

*Different lower-case letters indicate significant differences among means within the same row, whereas different capital letters indicate significant differences among means within the same column, using the protected LSD test, at $p \leq 0.05$

[#]Non-significant

of solid residues from MAP distillation in respect to pH increase-improvement.

As far as the EC is concerned (Fig. 2a, b), its increase was attributed to the increase of soil available nutrients especially that of macronutrients, as this is obvious from Tables 3 and 4. Similar findings are reported also by Deka et al. (2011) and Zhou et al. (2023), who attributed the EC increase to the release of available ammonium, phosphates and potassium. It is well known that application of organic materials to soil is expected to increase its salinity (Kumar et al. 2024; Zhou et al. 2023) and caution is needed to avoid salinity increase at risky levels. From that point of view the six- to tenfold increase of the initial soil EC, upon the 8%

application of flower-leaf residues from MAP distillation observed in this study (Fig. 2a, b), is somewhat concerning in respect to soil salinization risk and a good reason to avoid the 8% application rate.

Since, it is well known that soil CEC, apart from the clay mineralogy, depends also on the soil organic matter content and pH (Brady and Weil 2008), it would be reasonable to assume that soil pH increase upon the application of residues at the specific rates, as well as the organic matter addition to soil in the form of residues have contributed to the observed CEC increase (Fig. 3a, b).

It is well known that addition of plant residues with C/N ratio above 25 to soil, as the residues used in the present

study (Table 2), especially those of shoots, can cause N immobilization (Brady and Weil 2008; Sloom et al. 2022). However, although certain soil treatments had high values of C/N ratio, in all other soil treatments the C/N ratio ranged at levels like those of inorganic cultivated soils, i.e. 8–15, with a mean value of 12 according to Brady and Weil (2008) (Fig. 6a, b). Moreover, based on the results concerning soil available N (Tables 3 and 4), the values of C/N ratio of treatments did not adversely affect soil N mineralization, since the concentrations of soil available $\text{NO}_3\text{-N}$ increased from adequate to high levels in almost all treatments. In agreement with the findings of the current study, Kadodiglou et al. (2014) reported similar initial increases of the C/N ratio, for soil treatments with spearmint and sage tissues applied at rates like those of the current study, which vanished after 60 days of incubation. From all the above, it seems that the C/N ratio is affected by the incorporated species (e.g. flowers-leaves or shoots) and the rate of incorporation to soil (e.g. low or high), as well as by the sampling period (e.g. 30 or 60 days) (Chalkos et al. 2010; Kadodiglou et al. 2014).

Regarding soil fertility and begging with the soil available macronutrients, among the solid residues and application rates tested, those from the distillation of hemp, lavender and oregano applied at rates above 1% enhanced considerably soil available $\text{NO}_3\text{-N}$ (Tables 3 and 4). In all cases of treatments, the concentrations of soil available $\text{NO}_3\text{-N}$ ranged from adequate to high or very high levels, according to Dahnke and Johnson (1990) (sufficiency levels 10–19 mg kg^{-1}). Considering the results of both soil available $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$, it seems that all residues, apart from those of hemp, promoted the N nitrification over the N mineralization. As far as N mineralization is concerned, after summing up the total N of each residue added to soil at each rate with the initial soil total N and comparing these values with the determined total N of the respective treatments, N mineralization was evidenced for the treatments with flower-leaf residues from the distillation of helichrysum and rosemary and with shoot residues from the distillation of lavender at all application rates. Nitrogen mineralization was also evidenced for all other treatments, but not in a consistent way. Despite the above, Chrysargyris et al. (2023b) recommended N fertilization of soils together with the application of MAP residues, to balance N losses/utilization by microorganisms in the process of decomposition of MAP organic matter. The justification of such a recommendation was that the residues are considered unstable materials, which could cause decrease of crop yield, because of their high C/N ratio (above 25). However, such practice could be unnecessary in many cases and should be examined in relation to the nature of residues and the soil properties.

Like soil available $\text{NO}_3\text{-N}$, among the solid residues and application rates tested, those from the distillation of

hemp, lavender, oregano and additionally sage applied at rates above 1% enhanced substantially the soil available P (Tables 3 and 4). Soil available P, which was marginally sufficient initially, increased upon the application of the solid residues to sufficient or high (especially at the 4% rate) or very high (especially at the 8% rate) or even remained marginally sufficient (in certain cases of the 1% rate), according to Thomas and Peaslee (1973) (sufficiency levels 10–15 mg kg^{-1} and high levels above 20 mg kg^{-1}). All kinds of solid residues applied at all rates promoted soil available K (Tables 3 and 4). Moreover, soil available K concentrations were sufficient to high in control and increased to high levels upon the addition of residues, according to Haby et al. (1990) (sufficiency levels 150–200 and high levels above 200 mg kg^{-1}).

As far as the soil available micronutrients are concerned, it seems that only soil available B, Zn and Mn were consistently affected by the application of solid residues from MAP distillation (Tables 5 and 6). Furthermore, soil available B was marginally sufficient initially and increased to sufficiency levels upon the 2% application rate of the residues and afterwards, Cu was initially sufficient and remained at the same levels in all treatments, Zn concentrations were low and increased to sufficiency levels in all treatments, whereas Fe and Mn were high in control and remained at high levels in all treatments (Sims and Johnson 1991). Especially for Mn, its concentrations in all soil treatments including control could be considered as toxic, according to Fageria (2001).

In agreement with the findings of the current study concerning soil available macro- and micronutrients, Choularas et al. (2007) reported that an increased rate of added basil tissues to soil resulted in an increase of available macronutrients N, P and K, as well as micronutrients Zn and Mn. Moreover, according to Zaccardelli et al. (2021), composting of solid residues from sage distillation, rosemary and basil can produce a material suitable for the improvement of soil fertility. In addition, according to Kumar et al. (2024), enriched compost with solid residues of aromatic plants and low-grade phosphates and mica seemed to be more effective than traditional organic manures or similarly effective to conventional fertilizers in providing comparable amounts of available macronutrients to two alkaline soils. Furthermore, Chrysargyris et al. (2023b) noticed increased soil available nutrients with the addition of solid residues from distillation of oregano and sideritis.

On the other hand, although as it is reported MAP solid residues can enrich biochar, composts and soils with macro- and micronutrients, high application rates of these residues might cause adverse effects on plant growth and soil properties (Chrysargyris et al. 2023b, 2024; Kumar et al. 2024). This agrees with the findings of the current study,

concerning the excessive increases of soil available B and Zn upon the application of the solid residues from certain MAP distillation, at the 8% rate mainly and in some cases at the 4% rate. Regarding Mn, its initial high content in soil masked the effect of solid residues on its availability. Therefore, it seems that caution is needed in respect to risks of B, Zn and probable Mn phytotoxicities, which are common in acid soils, when solid residues from MAP distillation are used as soil amendments, especially in the case of B, for which the deficiency-sufficiency-toxicity levels are too close each other (Brady and Weil 2008).

5 Conclusions

The results of the study showed that the solid residues (especially those of flowers-leaves) from distillation of the medicinal and aromatic plants of hemp, helichrysum, lavender, oregano, rosemary and sage (especially those of hemp, and lavender) could be used as soil amendments-fertilizers for acid soils. Soil application rates higher than 1% of the residues can improve soil fertility, but the recommended rates for acid soils are those between 2 and 4%. Higher application rates of the specific residues to acid soils should be avoided, due to risks of soil salinization, N immobilization and B, Zn and probable Mn phytotoxicities. Moreover, application rates higher than 4% are not practical regarding the proper handling of the residues in the field. Furthermore, the flower-leaf residues from the distillation of the selected medicinal and aromatic plants (especially those of hemp) could be used as liming materials for strongly acid soils. Since this is a preliminary study, for the establishment of the agronomic use of the solid residues from the distillation of hemp, helichrysum, lavender, oregano, rosemary and sage, further investigation is needed in respect to their effects on soil fertility and microbial community and on plant growth, by means of at least pot experiments. In any case, the further investigation should focus on the flower-leaf residues and the 2–4% application rates to soil. In addition, the effect of essential oils contained in the specific residues on soil properties and plant growth should be investigated.

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Data Availability All data are included in the manuscript.

Declarations

Conflict of interest Authors have no conflicts of interest.

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