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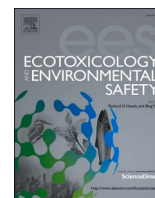
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Biochar–Compost blends modulate trace element and nutrient dynamics in rooftop farming systems under Mediterranean conditions

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ABSTRACT

The rising interest in Rooftop Agriculture (RA) has stemmed a demand for sustainable, lightweight alternatives to peat as plant growing media. Co-composting organic waste with biochar could represent a solution with reduced environmental impact. However, knowledge gaps remain regarding the food safety and environmental performance of these materials. This study examined trace element and nutrient dynamics in six substrates derived from three feedstocks: spent coffee grounds, coffee silverskin, and seaweeds, composted with and without biochar. Over three years, tomato (*Solanum lycopersicum* L., cv. Moruno de Aranjuez) and a mix of lettuce (*Lactuca sativa* L., cv. Romana) and Swiss chard (*Beta vulgaris* var. Cicla) were cultivated on a rooftop in central Madrid (Spain). To unveil the bigger picture behind element uptake by plants and leaching into drainage water, specific indices were calculated by grouping elements by risk-based categories. Results showed feedstock-dependent trace element and nutrient dynamics, with biochar reducing their plant uptake and leaching. Despite seaweed-based compost showing the highest arsenic levels, biochar lowered plant uptake by up to 40%. Cadmium and lead in edible parts varied by year and substrate, but they remained within EU safety limits. Atmospheric deposition minimally affected lettuce trace element content, while washing reduced hazardous elements. Biochar improved nutrient retention, reducing phosphorus and nitrogen losses by 40% and 25%, respectively, over three years. These findings underline the potential of biochar-amended composts as sustainable, safe peat alternatives for RA, supporting crop production while mitigating environmental and health risks.

1. Introduction

Urban Agriculture (UA) is drawing attention for its role in boosting nutrition and food security in local communities by offering a reliable source of local vegetables (Lal, 2017) while providing numerous additional ecosystem services such as heat mitigation, biodiversity enhancement and waste assimilation and recycling (Theodorou et al., 2020). Although UA's benefits are undeniable, urban farmers' challenges are significant. The limited availability of land, coupled with

competing demands for urban space, presents a major obstacle to expanding in-ground UA (Harada and Whitlow, 2020). Consequently, urban orchards are often relegated to marginal brownfields, generally affected by pollutants from human activities, such as industrial processes, traffic and heating systems (Jean-Soro et al., 2015).

Rooftop Agriculture (RA) has emerged as an innovative solution with great potential due to numerous social, environmental, and economic benefits (Appolloni et al., 2021). By cultivating unused city rooftops, RA contributes to the local production of vegetables through community

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engagement and, thanks to its elevated location, can prevent exposure to some contaminants from road traffic (Grard et al., 2020). RA, defined as a type of zero-acreage soilless farming systems, typically employs substrates that must be fertile, structurally stable, and lightweight enough to meet building structural limitations (Fussy and Papenbrock, 2022). Peat is the most widely used commercial cultivation medium; however, this non-renewable resource plays a crucial role in the global carbon cycle, which has led some countries to impose extraction limitations (Nordbeck and Hogl, 2024). This has intensified the search for sustainable alternatives, among which composted municipal organic waste stands out as a promising option. It provides a lightweight, nutrient-rich substrate while promoting circular economy principles and reducing pressure on waste management systems (Woldeamanuel et al., 2022). Nevertheless, urban waste-based compost requires ensuring a low presence of contaminants (trace elements in particular) and substrate stability over time (Grard et al., 2020). Trace elements (TE) refer to elements that are not so abundant in environmental matrices, such as metals like cadmium (Cd), lead (Pb), and zinc (Zn) and metalloids like arsenic (As), antimony (Sb), and selenium (Se), which can pose environmental and toxicological risks (Natasha et al., 2022). For the assessment of these composts, their phytoavailable fractions of harmful TE must be considered, as these can be readily absorbed by crops (Madejón et al., 2011), or mobilised by irrigation water, contributing to substrate depletion and metal dispersion (Harada et al., 2019; Kupper et al., 2014). In the urban environment, atmospheric deposition—referring to the settling of particles and gases from the air onto the surface of plants—can also influence the presence of TE in vegetables. For instance, Augustsson et al. (2023) pointed out that particles adhering to leafy vegetables significantly contribute to the plant concentration even after regular washing. The dietary uptake/assimilation of TE seriously threatens food safety, likely resulting in significant human health hazards (Izquierdo et al., 2015). This risk of contamination negatively restricts social acceptance and limits the adoption of UA, undermining the importance of local food production and practical solutions (Ziss et al., 2021). Additionally, rooftop gardens represent closed-loop systems, where substrate confinement could lead, over time, to TE accumulation, possibly increasing the final plant uptake.

Blending compost-based substrates with biochar (BC) has been proposed to balance nutrient load while minimising leaching (Sánchez-Monedero et al., 2021). Leaching plays a pivotal role in nutrient depletion within substrate systems, as it reflects the extent to which available nutrients are lost through water infiltration (Rashmi et al., 2017). BC is a highly recalcitrant, carbon-rich material characterised by both high porosity and cation exchange capacity (Goñi-Urriaga et al., 2022). These properties help stabilise organic substrates (Sánchez-Monedero et al., 2021) and enhance the retention and stability of nutrient and TE within substrates. This could also help to limit their translocation to plants and to minimise the environmental spread of major nutrients responsible for urban-originated eutrophication (Walters and Stoelzle Midden, 2018), which is driven by complex leaching dynamics (Wielemaker et al., 2019).

This study investigates the fate of TE, macro and micronutrients resulting from the use of biochar-blended substrates for horticulture derived from composted waste materials in an urban rooftop garden in a big city, Madrid (Spain), over three years. To facilitate fair comparisons across compartments (substrate, aerial and fruit biomass), three indices were calculated to standardize elemental concentration and group elements in three risk-based categories. It was hypothesized that the use of co-composted biochar as a substrate would be able to replace peat with waste-derived compost and mitigate hazardous trace element uptake by plants and mobility in urban environments, while maintaining similar effects on micronutrients.

2. Material and methods

2.1. Horticultural substrates made of biochar-blended composts

The feedstock materials used to prepare the growing media were spent coffee grounds (CG), derived from the institute's vending machines; coffee silverskin (CSK), provided by coffee-producing company Café Candelas SA (Lugo, Spain) and Supracafé (Móstoles, Spain) and seaweeds residues (S), which were collected from the Playa de la Costilla beach (Rota, Spain) during a period of hyperproliferation of the invasive species *Rugulopteryx okamurae*, which dominated the collected seaweed biomass. These feedstocks were selected for their high nutrient content, agronomic capacity, availability and environmental impact. Each of them was composted with green pruning waste (GW), provided by a local gardening company (Brunete, Spain), in the presence or absence of biochar (BC) as described in Table 1. The biochar was provided by the company Carbón Vivo SL (Barcelona, Spain), produced by pyrolyzing Aleppo pine (*Pinus halepensis*) pruning remains at 650–750 °C for 3.5 h (Handiso et al., 2024). A detailed description of the biochar main physical and chemical characteristics is summarized in Table S1. The elemental composition of the feedstock materials is provided in Table S2. Coffee silverskin is the tegument covering the coffee green bean that is separated during the coffee roasting process. Spent coffee grounds and coffee silverskin are the only coffee by-products generated in the consuming countries; positive agronomic characteristics of CSK and CSK-BC compost are reported in Picca et al. (2025). Similarly, the composting process of seaweed biomass with woody and carbon rich materials and the agronomic characterization of the end products are reported in Madejón et al. (2021). Based on this knowledge, we proposed the use of biochar-blended compost derived from these feedstocks as peat substitutes for horticultural substrates in rooftop farming.

Mixtures consisting of coffee by-products (CG and CSK) were composted at ICA-CSIC in 200 L composters equipped with a passive aeration system (HOTBIN composting, Northampton, UK), as described by Picca et al. (2023). Seaweed-based mixtures underwent composting in windrow piles at the composting plant “Compost Ecológico” (Rota, Spain) as described by Madejón et al. (2021).

After composting, all mixtures were processed using a garden shredder and then blended with a commercial peat-based substrate (Jiffy GO PP7, Jiffygroup) at a 50% (v/v) ratio, becoming the six growing media (or growing substrates, interchangeably for this study) tested in the rooftop farming experiment.

2.2. Experimental design

The experimental rooftop area was located on the ICA-CSIC building, in the centre of Madrid (Spain, 40°26'25.5"N 3°41'13.2"W) (Fig. 1). Composted organic wastes as growth substrates were placed in plastic pots of about 70 L volume, distributed on a modular framework constructed from wooden pallets and metal supports. The upper portion of

Table 1
Raw materials proportion utilised to obtain the six composting mixtures.

Raw materials	Composting mixtures					
	CG+BC	CG	CSK+BC	CSK	S+BC	S
	Volume in litres					
Coffee Grounds	38	38	0	0	0	0
Coffee Silverskin	0	0	38	76 ^a	0	0
Seaweed	0	0	0	0	50	50
Green Waste (GW)	38	38	38	38	50	50
Biochar (BC)	38	0	38	0	50	0
Ratio	1:1:1	1:1:0	1:1:1	2:1:0	1:1:1	1:1:0
Feedstock: GW: BC						

aCompost CSK started with a ratio 1:1 (v:v) of CSK and GW; a second dose of CSK was added halfway through the process (15 days) to overcome the compaction of CSK during composting, reaching a final CS:GW ratio of 2:1 (v:v).

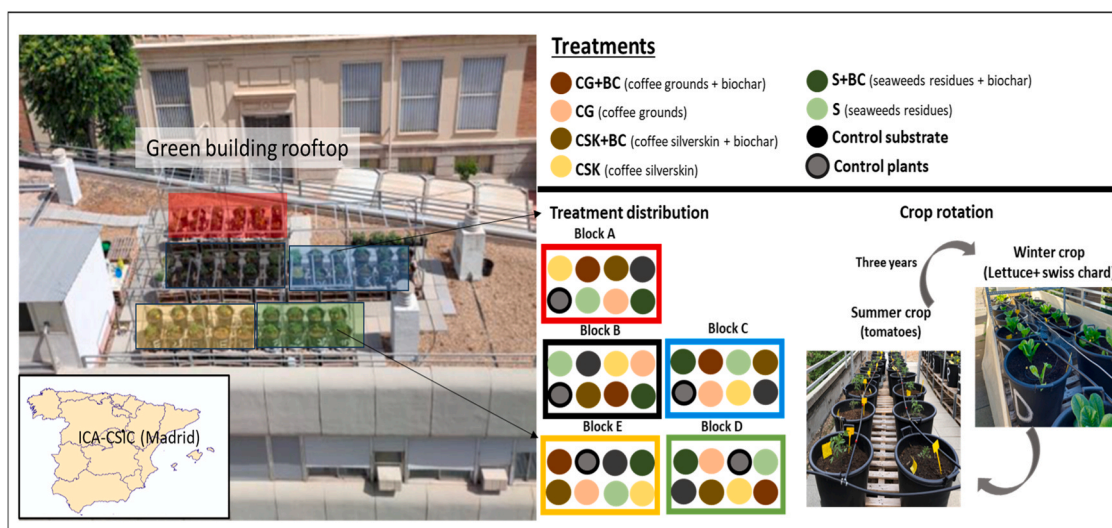


Fig. 1. Experimental design of the rooftop experiment located at the Institute of Agricultural Sciences (ICA-CSIC) in Madrid, Spain. The growing substrates used as treatments were made from composts proceeding from CG (spent coffee grounds), CSK (coffee silverskin), S (seaweed) residues, blended with or without BC (biochar).

the structure accommodated 35 randomly arranged plastic pots containing the tested substrates, each with five replicates, grouped into five distinct blocks (Fig. 1).

Then the growing substrates were placed into the plastic pots in two different structures following Grard et al. (2018): (i) for biochar-blended composts, a single layer of compost/peat mixture (33 cm) with a 5 cm drainage layer of BC at the bottom to prevent substrate loss during water flow; (ii) for substrates made from composts without biochar, a lower structural layer made of pure biochar (14 cm) was topped with the corresponding growing media (19 cm). A control treatment, made of pure peat-based substrate (Jiffy GO PP7, Jiffygroup) was also established within each block (hereafter the peat-based control will be referred to as 'peat' throughout the article).

Volume losses due to substrate compaction were compensated by refilling the same growing media to reach its original volume of the pots (ranging from 0 to less than 10 cm). Equal irrigation from tap water was supplied to each pot through a drip system using self-compensating drippers with a flow rate of 2 L/h (Irritec®).

To evaluate trace element leachates and the quality of water discharged into the sewage system, a 10-litre plastic tank was placed under blocks A, C, and D for leachate collection. The first cropping cycle presented some issues of the irrigation/leachate collection system, thus these data were not included in the final leaching assessment, while only data from the second and third year were included in the present study.

2.3. Crop rotation

Elemental composition variations resulting from plants (stem, leaves and fruits) uptake was studied over a three-year crop rotation cycle utilising a succession of a local conservatory variety of tomato (*Solanum lycopersicum* L., cv. Moruno de Aranjuez, registered according to the European Commission Directive 2008/62/EC and conserved at the Germplasm Bank of the Community of Madrid) in spring/summer, and a consociation of lettuce (*Lactuca sativa* L., cv. Romana) and Swiss chard (*Beta vulgaris* var. cicla) in autumn/winter. The experiment began in May 2021, corresponding to the start of the first agronomic year, and concluded in November 2023, encompassing three summer cropping cycles and two autumn/winter cropping cycles (Figure S1).

2.4. Sample preparation and analyses

2.4.1. Growing substrates

The substrates were analysed at the beginning (t0, initial time), middle (t12, t24), and end (t6, t18, t30) of the summer crop, where t0 corresponds to day 0, and the numbers (t6, t12, t18, t24, t30) indicate the number of months elapsed since the start of the experiment. A 100 g aliquot was randomly collected from five points at the first 0–15 cm depth of each pot, mixed to obtain a composite sample per pot and dried at 40 °C for three days. Substrates pH and electrical conductivity (EC) were measured in water extracts at a 1:10 w/v ratio using a CRISON microPH 2001 (Crison Instruments SA, Barcelona, Spain) and a CRISON microCM 2201 (Crison Instruments SA, Barcelona, Spain), respectively.

Afterwards, samples were finely grounded with a micro-whisk mill (Culatti AG, Steinerberg, Switzerland) equipped with a 2 mm mesh size sieve and characterised for elemental analysis.

Total carbon (C) and nitrogen (N) contents were assessed on substrates by dry combustion and gas chromatography using a ThermoFlash 2000 NC Soil Analyzer (Thermo Fisher Scientific, Waltham, MA, USA). The total composition, including macronutrients, micronutrients and TE in the composted substrates was assessed by digesting the samples with hydrochloric acid (HCl) and nitric acid (HNO₃) in a 3:1 (v:v) using a Mars One microwave (Allentium, Barcelona, Spain).

Phytoavailable nutrients in the growing substrates were assessed using the CAT (calcium chloride/DTPA) extraction method according to UNE-EN 13651. The extract was collected and stored at –20 °C prior to the analysis. Total and phytoavailable resulting extracts were then analysed with an ICP-MS Agilent 7800 (Agilent Technologies, Inc., Santa Clara, CA, USA) at the IRNAS-CSIC analytical service (Seville, Spain). The analytical service is part of the Wageningen Evaluating Programmes for Analytical Laboratories, WEPAL, for soils, plants and manures, assuring the quality of the sample digestion, extraction and analysis performed.

2.4.2. Plant and fruit biomass

Cultivated plant samples (tomato, lettuce and Swiss chard) were collected at the end of each cultivation cycle from each pot and pre-treated for further analysis. While for lettuce and Swiss chard the study was conducted on the aerial biomass, the tomato cropping comprised sampling of both aerial and fruit biomasses.

The collected tomato aerial biomass, consisting of a homogeneous 50:50 mix of about 500 g of stems and leaves, was dried at 65 °C for

three days to determine its dry weight. During the crop cycle, three tomatoes per plant were harvested, washed with distilled water, and dried at 65 °C for seven days.

For lettuce and Swiss chard, the total aerial biomass was collected for each pot, during the two different cropping cycles. To assess potential atmospheric contamination, each harvested lettuce was divided in half: one set was washed and thoroughly dried with paper cloth, while the other was processed unwashed. The oven drying of lettuce and Swiss chard followed the same procedure as for tomato aerial biomass. Finally, all samples were finely grounded using the same micro-whisk mill described above.

Total C and N contents were assessed on plant biomass by dry combustion and gas chromatography using a ThermoFlash 2000 NC Soil Analyzer (Thermo Fisher Scientific, Waltham, MA, USA).

Elemental composition in the plant biomass was determined after digestion in a digiPREP type heating block (SCP Science – AnalytiChem, Baie-D'Urfé, Canada Inc.) using HNO₃ using an inductively coupled plasma mass spectrophotometer (ICP-MS, Agilent 7800, Agilent Tech-

1. Potentially Dangerous (PD): Includes As, Cd, Hg, and Pb, elements with known toxicity even at low concentrations and no biological function.
2. Moderately Hazardous (MD): Includes Cr, Mn, Ni, U, and V, elements that may be essential or non-toxic at trace levels but are harmful at elevated concentrations.
3. Potentially Beneficial (PB): Includes elements like Al, B, Ba, Ca, Co, Li, Mg, Mo, Na, S, Sn, Sr, Cu, Fe, and Zn, elements generally considered important for plant or human metabolism and typically non-toxic within normal concentration ranges.

Index values were computed using a min-max normalisation (rescaling to 0–1 range, Eq. 1), as described in Mazzatorta et al. (2002) and Mazziotta and Pareto (2022). This standardization enabled comparison across treatments by adjusting for variation in element concentration ranges and highlighting feedstock-related differences.

$$\text{Standardised Value} = \frac{(\text{Element concentration} - \text{Minimum concentration value})}{(\text{Maximum concentration value} - \text{Minimum concentration value})} \quad (1)$$

nologies, Inc., Santa Clara, CA, United States) by the IRNAS-CSIC (Seville, Spain) analytical service.

All the edible biomass samples (tomato fruits, lettuce and Swiss chard plants) were harvested at the peak of ripeness for optimal consumption.

2.4.3. Leachates

The volume of leached water was measured for all treatments. At the time of 10 L tank filling, tanks were thoroughly shaken to homogenise the collected water and a sample of 100 mL was drawn from each tank (A, C, D), filtered with a 0.45 µm nylon syringe and then acidified with 2 mL of HCl to reach approximately pH = 2 to stabilise the elements' oxidation states, and stored at 5 °C until analysis. Subsequently, a 40 mL composite sample of each year was prepared from each block to assess TE content with an ICP-MS (Agilent 7800, Agilent Technologies, Inc., Santa Clara, CA, United States). N content of the leachates was measured with a Shimadzu TOC-V SCH instrument (Shimadzu Corporation, Kyoto, Japan).

2.5. Data processing and statistics

2.5.1. Indices of elements pathways in substrates and biomass

To evaluate the evolution of TE and nutrients across substrates, aerial biomass, and fruit biomass, three indices were calculated at times t₀, t₁₂, and t₂₄: the Substrate Concentration Index (SI), the Aerial Biomass Translocation Index (T_{aerial}), and the Fruit Biomass Translocation Index (T_{fruit}). These indices were used to assess: (I) whether the evolution and translocation of elements were feedstock-dependent, (II) the modulating role of biochar on these dynamics, and (III) how these effects evolved over time. To facilitate interpretation, the studied elements were grouped into three categories based on their physiological relevance and potential risk to human health. These categories were defined using criteria adapted from internationally recognized sources, including the World Health Organization (WHO, 2016), the European Food Safety Authority (EFSA, 2009; 2021), and the Food and Agriculture Organization (FAO, 2016). While no universal classification scheme exists, the grouping adopted in this study reflects a synthesis of risk-based and nutritional significance commonly used in environmental and food safety assessments. The categories were:

2.5.1.1. *Index of element concentration in the substrates.* Specific indices were calculated for the three risk-based categories SI_PD, SI_MD, and SI_PB explained above. Each index corresponds to the sum of normalized values of the elements assigned to the categories, whereas the total substrate index (SI_{Total}) corresponds to the sum of normalized values for all measured elements.

2.5.1.2. *Translocation indices to aerial and fruit biomass.* The T_{aerial} and T_{fruit} were calculated to assess the mobility and dynamics of TE within the different plant parts. Before applying the rescaling step (Eq. 1), each element concentration in plant biomass was normalised to the corresponding concentration in the substrate at the beginning of each agronomic year (t₀ for year 1, t₁₂ for year 2, and t₂₄ for year 3). This normalisation ensures comparability of translocation efficiency across different time points and plant types by accounting for the initial substrate availability of each element. The normalisation formula is adapted from approaches used in nutrient use efficiency and phytoavailability studies (e.g., McLaughlin et al., 2011; Kabata-Pendias, 2010), and is expressed as follows: to ensure consistent translocation across different time points and plant types (Eq. 2).

$$\text{Biomass normalisation} = \frac{C_{\text{aerial}_i}}{C_{\text{substrate}_{t_i}}} = \frac{(C_{\text{aerial}_i \text{ tomato}} + C_{\text{aerial}_i \text{ lettuce}} + C_{\text{aerial}_i \text{ chard}})}{C_{\text{substrate}_{t_i}}} \quad (2)$$

where, C_{aerial_i} is the total concentration of each element *i* (mg kg⁻¹) obtained from the sum of its content in tomato, lettuce and Swiss chard aerial biomasses across the first and second year treated independently. The third year ended with the tomato cultivation, thus only C_{aerial_i tomato} content was considered for that period. C_{substrate_{t_i}} is the concentration of element *i* (mg kg⁻¹) in the substrate at the start of each year.

After normalisation, the element standardisation procedure as explained above in Eq. 1 was undertaken. The total aerial biomass translocation indices (i.e T_{aerial_{total}}, T_{aerial_{PD}}, T_{aerial_{MD}}, T_{aerial_{PB}};) summarise the standardised values of all elements, as PD, MD and PB categories and the total sum of all the three categories.

The translocation indices to fruit biomass T_{fruit} were calculated similarly to the aerial biomass indices, but for each studied year, only tomato fruit element concentrations were considered, which were then

normalised by the substrate concentration, scaled, and categorised into T_fruit_total, T_fruit_PD, T_fruit_MD, T_fruit_PB. For the first year, Cd was excluded from the analysis of the tomato fruit biomass due to analytical issues that impeded the quantification of this element.

These indices help to track the movement of elements from the growing substrates to different plant parts, offering insights into how these elements are distributed between the aerial biomass and fruits depending on feedstock, biochar blending, evolution with time and plant active discrimination of elements.

2.5.2. Leachate contribution to substrate depletion

The evaluation of substrate depletion involved the quantification of element losses through leaching. For each element, the yearly total mass loss was calculated as shown in Eq. 3, using the average element concentration and the total leached volume for each season. Furthermore, the contribution of each element over the total leached content was quantified (Eq. 4), in order to identify main leaching drivers.

$$Total\ leachate\ by\ season(mg) = \sum (Element\ concentration \left(\frac{mg}{L}\right) \times Leachate\ volume(L)) \quad (3)$$

Percentage of leaching for each element

$$= \frac{Average\ leached\ element}{Total\ leaching} \times 100 \quad (4)$$

The normalisation approach used in Eq. 4 is based on standard procedures for expressing relative contributions in leachate analysis (e.g., Kabata-Pendias, 2010; Sparks, 2003). This method allows to compare element losses relative to the total leached mass, minimizing bias due to differences in element concentrations or volumes.

2.5.3. Statistical analysis

Changes in TE concentrations within the substrates over time were visualised using Non-linear Multidimensional Scaling (NMDS) analysis, known to be effective in highlighting temporal trends (Bialik et al., 2021), making it ideal for investigating the impact of crop successions from 2021 to 2023. To further explore the role of physical and chemical properties, substrate pH and EC were correlated to the NMDS axes using permutational multivariate analysis of variance (PERMANOVA), highlighting their relationship with temporal dynamics.

Linear mixed effects models (LMM) with blocks as the random factor

were used to examine the differences among the different indices. This approach was appropriate for controlling spatial variability and accounting for repeated measurements within blocks. Significant differences among treatments were further examined by comparing estimated marginal means using Tukey’s post-hoc tests at a 0.05 significance level (emmeans and cld functions in R). One-way ANOVA was used to detect differences in mean element concentrations across feedstock types (PD, MD, PB), leached elements, and macronutrient (NPK) dynamics at each sampling time. The assumptions of normality and homogeneity of variance were tested and met, validating the use of parametric tests in these cases. To evaluate the specific effect of biochar addition within each feedstock type, independent samples t-tests were applied, offering a straightforward comparison between blended and non-blended substrates. A repeated-measures ANOVA was conducted to analyse changes in pH and EC over time, accounting for the within-subject correlation of longitudinal data. In cases where assumptions for parametric tests were not met, such as in the evaluation of potential atmospheric contamination risks, the non-parametric Mann–Whitney test was used. Finally, Principal Component Analysis (PCA) was employed to reduce the dimensionality of the dataset and explore patterns among substrate physical and chemical properties, total index values (for substrate, biomass, and fruit), and the phytoavailability of elements at the beginning of each cropping cycle (t0, t12, t24). All statistical analyses were performed using R version 4.2.3 (R Core Team, 2023) and SPSS v25 for Windows (IBM Corp., Armonk, NY, USA).

3. Results and discussion

3.1. Shifts in elemental composition and the role of pH and electrical conductivity in substrate differentiation

The NMDS clustering showed that the evolution over time of nutrient and trace element concentrations was substrate-specific (Fig. 2).

In general, substrates from the same feedstock tended to cluster together independently of the biochar addition, although its inclusion moderated and stabilized EC throughout the experiment. The NMDS plot displayed a clear separation between samples collected at the beginning (2021) and at the end (2023) of the experiment, primarily along the horizontal axis (NMDS1), which was very significantly correlated with substrate pH (PERMANOVA, F= 0.73, p < 0.001). Initial pH values (t0) ranged from 5.9 to 7.1, within the optimal range for the cultivated

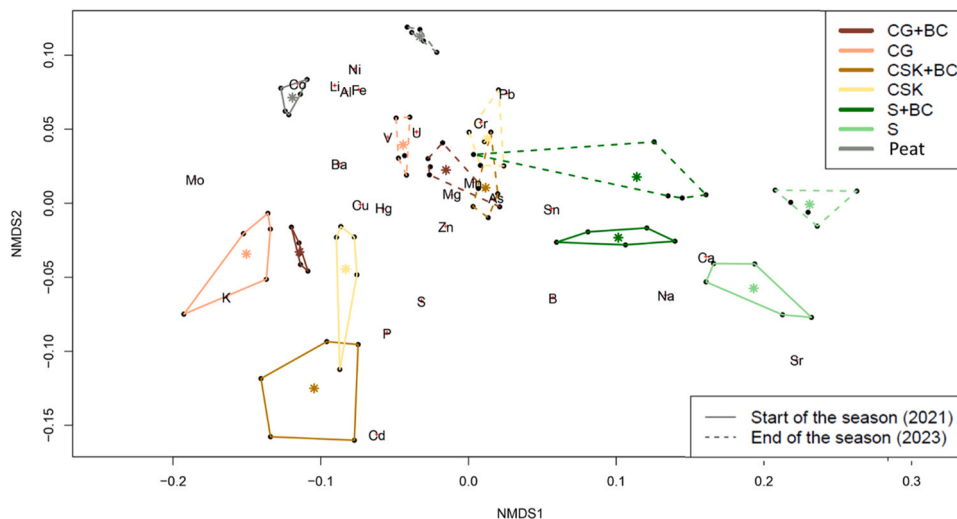


Fig. 2. NMDS ordination plot showing the centroids, polygonal hulls and observations illustrating the relationship among the growing substrates (CG: coffee grounds, CSK: coffee silverskin, S: seaweed; BC: biochar; peat: peat-based control) and total concentration of major and trace elements (Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sn, Sr, U, V, Zn) at the start of the 2021 (continuous line) and the end of the 2023 (dashed line). Non-metric goodness of fit (Shepard’s diagram) R² = 0.99 and stress value = 0.0724 met the general criteria for good NMDS performance.

species (Hemphill and Jackson, 1982; Dyško et al., 2009), and substrate pH values were consistently higher than those of the peat-based control, particularly in the seaweed substrates (Table S3). The incorporation of biochar resulted in an increase in pH in both the CSK and CG substrates; in contrast with the S substrate. Over time, a slight rising trend in pH was recorded across treatments. This finding aligns with the observations made in our study and can be attributed to the release of alkaline compounds from biochar and the decomposition of organic matter. These processes likely contributed to changes in nutrient availability, as higher pH values reduce the solubility of metals while increasing the availability of certain metalloids. This phenomenon appears most distinctly in the CSK and CG treatments, where shifts in pH were associated with diminished metal mobility. The observed increase in pH, in conjunction with repeated cropping cycles, may have further influenced nutrient dynamics, as previously reported in previous studies (Madejón et al., 2021; Ahmad et al., 2017; Barrow, Hartemink, 2023).

The vertical axis (NMDS2), which correlated very significantly with EC (PERMANOVA, $F = -0.622$, $p < 0.001$), added a further level of differentiation, indicating that variability in ionic availability in the solution was also a key factor influencing substrate evolution. Substrates' EC values were significantly higher than the peat (Fig. 2, Table S3), whereas biochar addition reduced EC values by 40 % in CSK, 35 % in CG, and 12 % in S, compared to treatments without biochar. This aligns with findings by Park et al. (2021), who suggested that biochar can lower EC in compost mixtures by adsorbing dissolved ions.

These pH and EC drive the NMDS ordination, in which substrate clustering was feedstock-derived independently of biochar addition. CG, CSK and the peat-based control showed the most pronounced separation of their centroids between 2021 and 2023, implying a substantial shift in elemental composition in these substrates over time, which was less evident for S treatments. The addition of biochar appeared to modulate the shifts along NMDS1 through changes in pH and EC, which were the main drivers of substrate differentiation. This confirms the role of BC as a modulating factor of the behaviour of TE in various environments (Sun et al., 2022).

3.2. Indices evolution and elemental content in substrates, plants, fruits and leachates

3.2.1. Total contents in substrates

In general, alternative growing substrates made of composted feedstock showed similar levels of both contaminants and nutrients compared to peat. The ranking of substrates determined by their SI_PD index remained consistent across the cropping cycles (Fig. 3). Seaweed-based substrates, especially those without biochar, had significantly higher SI_PD compared to the other treatments during the first year, however SI_PD was still the highest but similar to the peat-based control at the end of the experiment. This trend was consistent also for SI_MD and SI_PB indices.

In the first year, the peat had SI_PD values that were 160 % lower than the S treatment and 200 % higher than the average values of the coffee-based substrates, whether or not biochar was added to the latter ones. By the end of the experiment, the peat halved its SI_PD value compared to the first year, resulting in a significantly lower PD value (42 % less) than the S treatment, but almost 6 times greater PD value than CSK+BC treatment (Fig. 3).

The higher SI_PD for seaweed-derived substrates was driven by significantly larger levels of As and Pb, up to 41 % higher than the average levels in other treatments. Levels of Cd for seaweed-derived substrates were up to 49 % higher compared to the other treatments, but with a larger data dispersion (Figure S2). Similarly, for SI_MD elements, S treatment had significantly increased Mn levels by 28 % compared to the average of the other treatments, being very similar to the peat. For SI_PB elements, the elements Ca, Fe, Al, and Mg were the most abundant in this order. Biochar addition significantly increased Al levels (Figure S2), whereas Ca and Mg were more abundant in seaweed-

based substrate, and Fe was most concentrated in the peat control.

Seaweed-based substrates presented elevated TE concentrations, most likely due to the marine sand accumulation in their biomass, together with their ability to absorb TE from the surrounding environment (González Fernández et al., 2023). Despite certain elements being naturally abundant in the seaweed used in this study, the final SI_{total} was similar to the peat control suggesting that seaweed-based substrates can be as good as peat for soilless cultivation (Cole et al., 2016).

The addition of biochar to various composted feedstocks generally decreased the concentrations of PD elements, particularly As and Pb, compared to treatments without biochar (Figure S2), due to biochar's capacity to reduce both the total concentration and phytoavailability of TE. In fact, biochar derived from low TE content feedstocks contributes minimally to these elements, overall reducing concentration in composted mixtures and in the derived growing media (Wang et al., 2020). However, unlike SI_PD elements, the total concentration of SI_MD elements increased in CG and CSK substrates amended with biochar, suggesting that in this case, biochar acted as a source of TE rather than a diluting agent—though concentrations remained below those observed in peat. This outcome underscores the critical role of biochar feedstock selection, as its composition can significantly influence the input of both beneficial and potentially harmful elements. As previously reported, biochars derived from certain materials may release moderate levels of TE depending on their origin and production conditions (Conz et al., 2017).

3.2.2. Elemental translocation to aerial and fruit biomass

The translocation of elements from substrate to aerial biomass and fruits depends on multiple factors, including plant physiology, substrate composition, and environmental conditions (Cobb et al., 2000; Singh et al., 2010; Gupta et al., 2019), and the preferential uptake of beneficial elements over harmful ones remains a major challenge, due to the overlapping nutrient physiological pathways (Kaur et al., 2016).

During the experiment, fruit translocation patterns generally mirrored those of aerial biomass across years, regardless of substrate. The T_{aerial} PD index varied notably with year and substrate, reflecting the substrate's evolution over time (Fig. 3). Among the elements analysed, As showed the most pronounced differences in aerial uptake across substrates, with its concentrations in plant biomass closely reflecting those measured in the substrates (Figure S2 and S3). Notably, plants cultivated in seaweed-based substrates accumulated significantly higher levels of As compared to both the control and other substrates; however, this effect was mitigated by biochar addition. However, the PD elements' aerial translocation in the seaweed substrates remained generally lower than in the other substrates (Figure S3). The same trend was observed for PD translocated to fruits. Although seaweed-based growing media had the highest PD elements concentration in the substrates, this did not result in higher aerial or fruit biomass translocation, remaining within the Spanish and EU standards (Commission Regulation (EU) 2023/915) regulatory limits. In fact, for tomatoes, elements like As, Cd, and Pb accumulate preferentially in roots rather than fruits (Cobb et al., 2000).

Regarding Cd and Pb, their primary sources were identified as the substrates themselves, which initially (t₀) presented similar concentrations of these elements, comparable to the peat-based substrate. In contrast, coffee-based substrates showed significant T_{fruit} PD values, particularly in the third year, with translocation rates 57 % higher compared to the seaweed substrates. In this case, coffee-based substrates showed greater variability of Cd and Hg concentrations (Figure S3), probably due to the co-absorption of Cd with other divalent cations with a plant nutrient role, such as Ca and Mn (Lima et al., 2019). This trend was more prominent in the second year but decreased in the third one, likely due to a depletion of the total pool of cations and/or a reduced phytoavailability mediated by the observed increase of the substrate pH and the decrease of EC (Kicińska et al., 2022).

Seaweed-based treatments consistently showed the lowest MD and

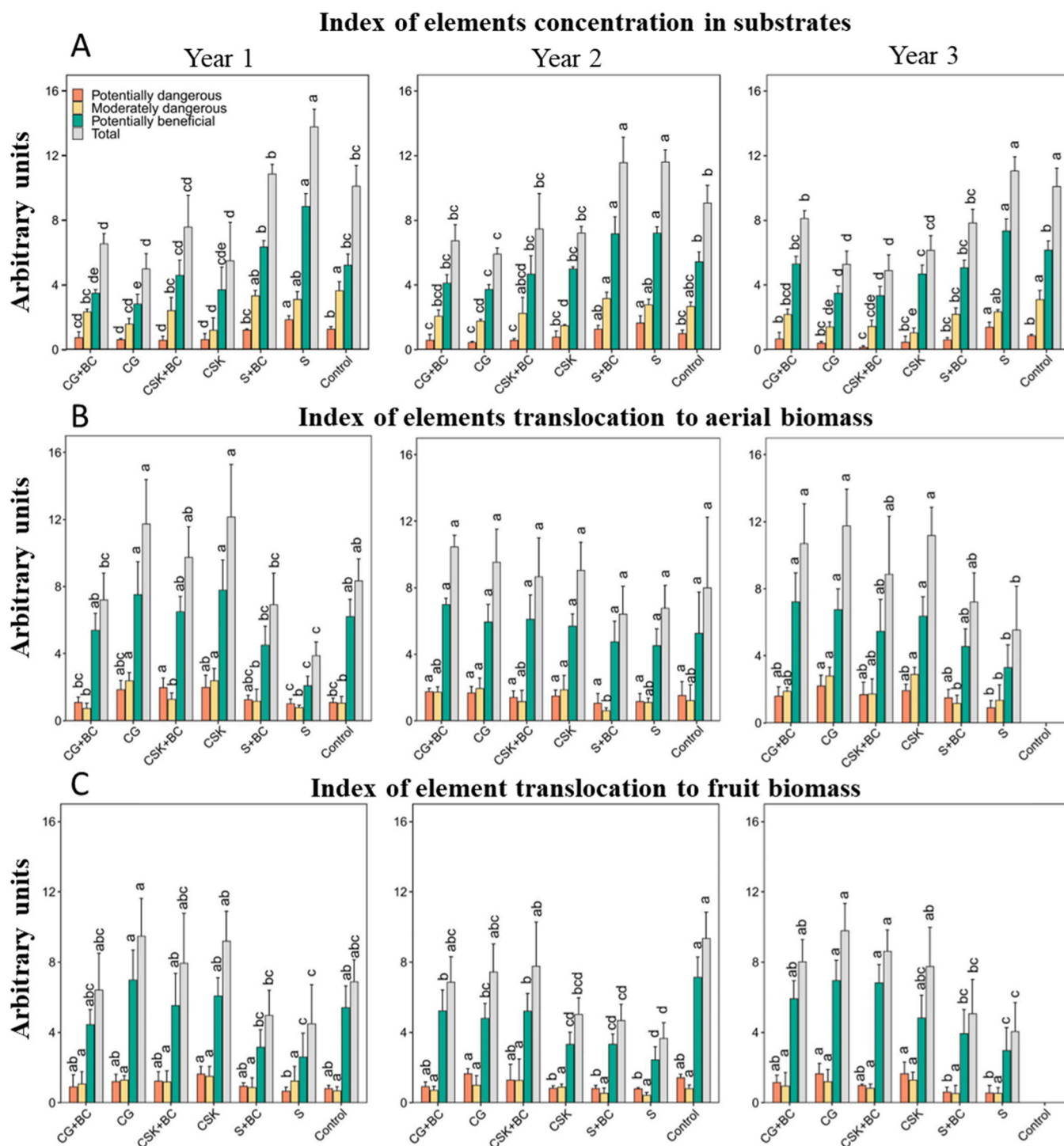


Fig. 3. A) Index of total concentrations of major and trace elements in different substrates (CG: coffee grounds, CSK: coffee silverskin, S: seaweed; BC: biochar; peat: peat-based control) at the beginning of each agronomic year coinciding with tomatoes cropping (t0, t12, t24). B) Index of total concentration of major and trace elements from the growing substrates translocated to the aerial biomass (tomato plant, lettuce and Swiss chard for the first and second years, only tomato for the third year) normalised by the concentration in the substrates at the beginning of each agronomic year. C) Index of total concentrations of major and trace elements from the growing substrates accumulated to the tomato fruits biomass normalised by the concentration in the substrates at the beginning of each agronomic year. Elements were categorised into: i) potentially dangerous (PD: As, Cd, Hg, Pb), ii) moderately dangerous (MD: Cr, Mn, Ni, U, V), iii) potentially beneficial (PB: Al, B, Ba, Ca, Co, Cu, Fe, Li, Mg, Mo, Na, S, Sn, Sr, Zn), and iv) the total sum of all three categories. Due to analytical issues, Cd values were not available for tomato fruits collected during the first year. Data were standardised within each category using min-max scaling procedure. For Figs. B and C element concentrations of the samples were previously normalised by substrate contents (see 2.4 for details).

PB index both in aerial and fruit biomass, indicating an effective reduction in the uptake of the corresponding elements. Translocation of MD elements to fruits, however, was more stable than in the aerial biomass across years and treatments, suggesting steady physiological regulation (Kabata-Pendias and Szeke, 2015; Zhou et al., 2016).

In addition to the feedstock-driven translocation dynamics, biochar modulated the uptake of PD and MD elements, reducing their uptake in the first year of growth. However, this effect diminishes in subsequent years, suggesting that biochar's modulation effect on nutrient leaching could diminish over time as its reactive surfaces degrade or become saturated (Alkharabsheh et al., 2021).

In the first year, coffee-based substrates without biochar showed higher PB translocation to fruits. However, in subsequent years, substrates amended with biochar exhibited increased PB values, suggesting an initial sequestration effect of biochar followed by a gradual nutrient release that promotes more stable uptake patterns over time. Biochar ageing—through oxidation, pore exposure, and surface accumulation of soluble organics—enhances its adsorption capacity, influencing nutrient translocation to biomass and fruit (Hagemann et al., 2017; Wang et al., 2020). These processes improved nutrient stability, particularly in fruits, as observed in similar studies (Rajkovich et al., 2012).

3.2.3. Substrate depletion over time

Depletion of macro and micro-nutrients from growing substrates is a function of both plant uptake and leaching to drainage water. On average, across the second and third year, the leaching of Ca, Na, Mg, S, N, P and K accounted for 99 % of the total elements leached, representing the main leaching contributors. Ca was the dominant element leached from all substrates, with consistently high levels in peat-control and CG substrates, showing only slight yearly variations (Table 2 and S4).

The dynamics of N and K leaching observed align with substrate-specific nutrient release and retention patterns. The increase in N leaching during the second year, paired with the significant drop in K leaching in the third year, highlights temporal shifts potentially influenced by biochar and compost interactions. Biochar's role, although modest and dependent on both the substrate and sampling time, supported nutrient retention, particularly for Ca, S, P and K, with leached percentages comparable to peat. In fact, biochar's cation exchange properties can mitigate leaching while maintaining overall K availability over time (Doulgeris et al., 2023).

The micronutrients leaching behaviour reflects the macronutrients total content observed in the substrates, where the feedstock materials were the primary influence (Fig. 4, Table S6).

An increase of phytoavailability of macronutrients is often paired with increased leaching, while non-available forms (e.g., organic P and

N, or precipitated K salts) may become mobilised over time due to mineralization of organic matter or pH acidification (Kabata-Pendias, 2010).

Compost-based substrates generally had higher macronutrients concentrations compared to the peat control for the majority of sampling periods. Total leached N showed the greatest variability across substrates, dropping quickly by the end of the first year (t6) for most of the substrates, but recovering to initial levels by t12, which could be explained by the interplay of N losses (uptake, lixiviation and mineralization cycles), N gains through microbial fixation of atmospheric N₂, and the concentration effect consequent to the mineralization of organic carbon (Cambardella et al., 2003; Clough and Condon, 2010).

Except for peat, total P contents across years followed similar patterns for all the treatments. The CG treatment had significantly lower P levels at the end of the experiment compared to the other treatments (Table S4). Compost-based substrates and peat showed similar patterns of shorter cycles of depletion and enrichment of total K. Compared to their initial levels, CG and S substrates showed the greatest losses in K over time, with reductions of 40 % and 25 %, respectively.

As previously discussed, biochar incorporation had a relatively moderate effect on the micronutrients and TE dynamics in substrates derived from the same feedstocks. By the end of the experiment, substrates amended with biochar generally exhibited lower N concentrations compared to their initial values, but still higher than those observed in the peat-based control. Among these, the CSK and CG treatments showed the highest N content. Additionally, K levels were consistently elevated in the biochar-amended substrates, explaining in fact their higher leaching. For P contents, biochar seemed to buffer P losses for coffee-based substrates when comparing the initial and final P values, from 23 % to 3 % for CG and CG-BC, and from 26 % to 10 % for CSK and CSK-BC, respectively. The S treatments had an average P loss of 16 %, showing no apparent effect of biochar. This evidence suggests that treatments with biochar tended to show better resilience and stability over time concerning macronutrients levels, confirming previous findings (Schmidt et al., 2021; Lehmann and Joseph, 2024). This stability from biochar addition is key for long-term fertilization in rooftop agriculture, where substrates are reused across cropping cycles and rarely renewed due to economic constraints (Grard et al., 2020). Furthermore, biochar's nutrients retention can mitigate their leaching into urban waters and subsequent contamination of close water basins, limiting the contribution of RA to eutrophication processes (Smith et al., 2020; Vasseghian et al., 2024).

3.2.4. Interactions between substrate properties, total indices and elements phytoavailability

A PCA was carried out with the aim to disclose the complex

Table 2

Percentage of main elements leached with respect to the total in different substrates (CG: coffee grounds, CSK: coffee silverskin, S: seaweed; BC: biochar; peat: the peat-based control) during second (2022) and third (2023) year. Substrates marked with different letters differ significantly ($p < 0.05$) according to one-way ANOVA. Asterisks (*) indicate significant differences within each substrate due to biochar addition, as determined by a *t*-test.

Leachate (%)	CG+BC	CG	CSK+BC	CSK	S+BC	S	Peat
Ca	2022	36.6 ± 3.63 ^{ab*}	48.4 ± 2.96 ^b	36.5 ± 4.22 ^a	28.8 ± 3.61 ^{ab}	38.5 ± 3.06 ^{ab}	50.9 ± 9.18 ^b
	2023	39.7 ± 2.1 ^{abc*}	49.8 ± 1.61 ^{de}	37.2 ± 3.44 ^a	33.8 ± 1.78 ^{ab}	47.3 ± 1.49 ^{cd}	56.9 ± 1.96 ^e
Na	2022	12.0 ± 0.62 ^{ab}	10.5 ± 0.74 ^{ab}	12.3 ± 2.36 ^a	8.70 ± 1.11 ^{ab}	18.4 ± 0.09 ^{cd}	14.1 ± 2.04 ^{bc}
	2023	19.5 ± 3.10 ^a	18.4 ± 3.48 ^a	19.0 ± 1.72 ^a	12.1 ± 2.80 ^a	20.4 ± 4.71 ^a	18.7 ± 3.66 ^a
Mg	2022	8.87 ± 0.54 ^a	7.82 ± 2.47 ^a	9.47 ± 1.23 ^a	8.30 ± 0.59 ^{ab}	12.1 ± 1.32 ^{ab}	13.2 ± 0.44 ^{ab}
	2023	10.6 ± 0.39 ^a	6.62 ± 4.32 ^a	8.50 ± 1.88 ^a	7.97 ± 0.45 ^a	13.1 ± 1.54 ^a	12.9 ± 0.24 ^a
S	2022	5.21 ± 0.49 ^a	4.20 ± 0.07 ^a	7.23 ± 1.10 ^{a*}	4.38 ± 0.24 ^a	17.3 ± 1.36 ^b	17.2 ± 1.01 ^b
	2023	7.35 ± 1.61 ^{ab}	5.82 ± 0.33 ^a	8.77 ± 1.84 ^a	5.89 ± 0.68 ^{abc}	12.3 ± 1.99 ^c	11.0 ± 1.23 ^{bc}
N	2022	8.03 ± 0.36 ^c	6.09 ± 0.95 ^{bc}	5.76 ± 1.06 ^c	8.15 ± 2.16 ^{bc}	3.43 ± 0.55 ^{ab}	3.88 ± 0.50 ^{ab}
	2023	15.1 ± 2.45 ^{a*}	6.89 ± 2.59 ^a	10.6 ± 0.94 ^a	16.0 ± 5.46 ^a	5.28 ± 3.42 ^a	8.74 ± 5.39 ^a
P	2022	2.28 ± 0.52 ^{bc}	2.77 ± 1.27 ^c	0.56 ± 0.29 ^{abc}	1.08 ± 0.21 ^{ab}	0.59 ± 0.17 ^{ab}	0.40 ± 0.10 ^a
	2023	0.50 ± 0.24 ^a	0.91 ± 0.63 ^a	0.23 ± 0.08 ^a	0.54 ± 0.18 ^a	0.41 ± 0.24 ^a	1.19 ± 0.54 ^a
K	2022	26.6 ± 3.87 ^d	19.8 ± 2.07 ^{cd}	27.8 ± 4.18 ^{e*}	40.3 ± 2.62 ^d	9.38 ± 1.76 ^{ab*}	16.5 ± 3.06 ^{bc}
	2023	6.81 ± 4.59 ^{ab}	11.2 ± 1.82 ^{bc}	15.4 ± 2.70 ^{d*}	23.4 ± 0.74 ^c	0.77 ± 0.36 ^{a*}	2.08 ± 0.28 ^a

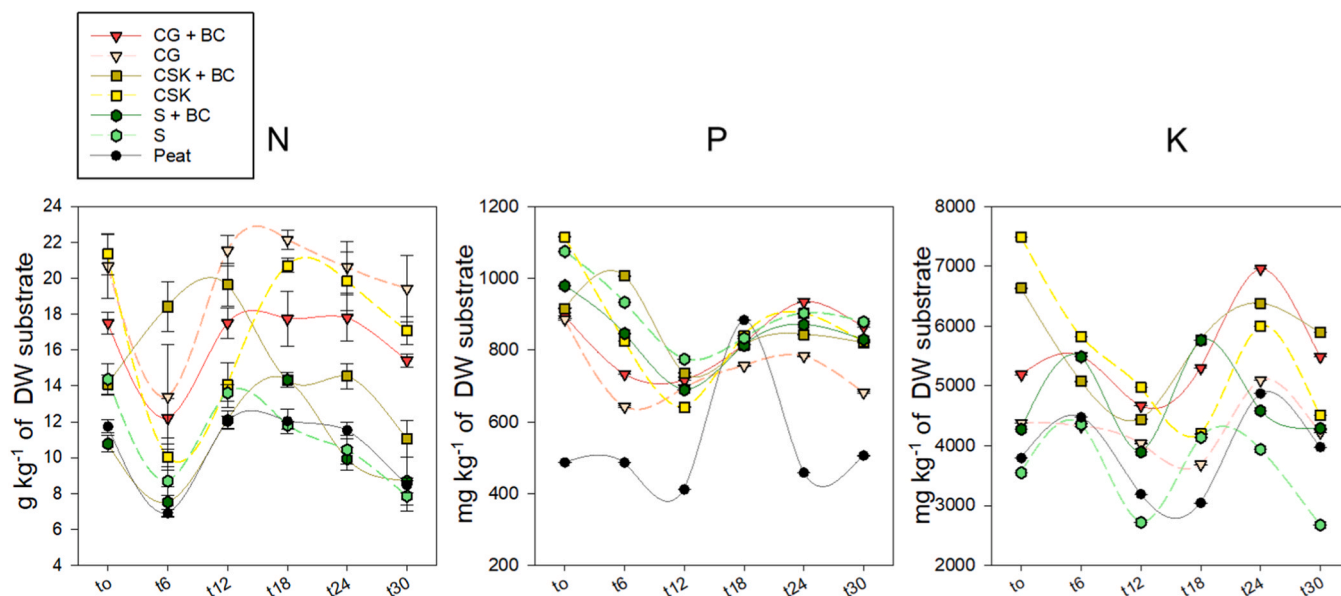


Fig. 4. Evolution of total N, P and K contents during the sampling campaigns (t0, t6, t12, t18, t24, t30) in different substrates (CG: coffee grounds, CSK: coffee silverskin; S: seaweed; BC: biochar; peat: peat-based control). Statistical analysis is reported in Table S5.

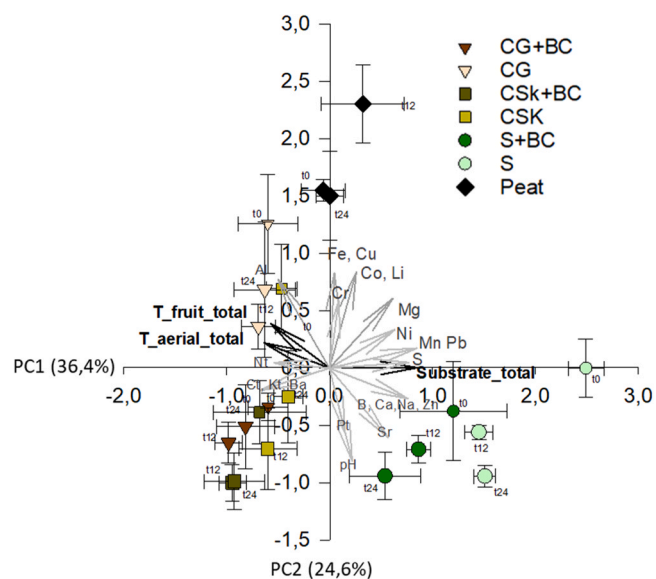


Fig. 5. Correlation bi-plot from the principal component analysis (PCA) on substrates physical and chemical variables, total indices and phytoavailable elements in the different substrates (CG: coffee grounds, CSK: coffee silverskin, S: seaweed; BC: biochar; peat: peat-based control) at the start of each cropping cycle (t0, t12, t24). Correlations of substrate properties with the main axes are given by arrows and habitat types by cluster centroids (average score on each horizontal principal component (PC1) and vertical principal component (PC2) with standard errors). Total carbon: Ct, total nitrogen: Nt, total potassium: Kt, total phosphorus: Pt. indices of total elements (PD, MD, PB) in substrate and biomasses are given by bold arrows (see paragraph 2.4 for the details).

interactions between the physical and chemical properties of the substrates, the proposed indices and the phytoavailability of the elements, which affected element translocation within the plant system.

Using the obtained data for all samples in the different substrates at the start of each cropping cycle (t0, t12, t24), the PCA identified two principal components (PC) which, together, explain 61.2 % of the total variance within the dataset (Fig. 5). SI_{total}, total C, and available Mn, Na, S, correlated significantly with the positive axis of PC1, Cu and Fe

correlated significantly with the positive axis of PC2, whilst Al, B, Co, Li, Ni, Pb, Zn, pH correlated significantly with both PC1 and PC2 (filtering the correlation to include only those with an $r^2 > 0.7$ and $p < 0.001$). Variables such as EC, Cd, Pavail and Kavail were excluded from the PCA analysis for having communality values < 0.1 . Tested treatments exhibited different clusters, strongly influenced by the starting feed-stock: S and coffee-based substrates were positioned in the different quadrants, with the more striking difference for biochar-free CG which diagonally opposed the seaweed substrates. The CG substrate is the only one closely positioned to peat, especially at t0, which resulted in stronger association with PC2, differently from the other substrates appearing closer to PC1. Overall, the PCA indicated specific positioning for phytoavailable elements such as B, Ca, Na, and Zn that were on the right of the PCA plot, in proximity to the SI_{total} index (Fig. 5), while diagonally opposing T_{fruit} total and T_{aerial} total. This suggests that these elements are predominantly associated with the substrate itself rather than being readily translocated into biomass or fruit. In contrast, phytoavailable elements such as Fe, Cu, Co, and Li were located in the upper right quadrant, along the same PC1 as T_{aerial} total and T_{fruit} total vectors, potentially indicating greater mobility and potential translocation to plant tissues. Previous research has shown that elements with higher affinity for plant uptake often display such clustering near plant tissue vectors, being more likely to be absorbed and accumulate in biomass or fruit over time (Kabata-Pendias, 2010).

The close positioning of T_{aerial} total and T_{fruit} total vectors in the left quadrant suggests a strong association between the accumulation of certain TE in both fruit and biomass specifically in the CG treatment. This pattern indicates that elements are translocated from the substrate into the plant without a strong discrimination between vegetative and reproductive tissues, consistent with studies on element uptake dynamics in agricultural substrates (Kabata-Pendias and Mukherjee, 2007). Furthermore, the T_{aerial} total and T_{fruit} total vectors are located in the left quadrant closer to the total concentration of macronutrients like N, and K. This relationship indicates that when large quantities of macronutrients are present in the substrate, plants can also establish a consistent pathway of micronutrients translocation. The fact that these are also related with Total C indicates that higher organic matter content is crucial for plant development, since it is associated with large pools of macro- and micronutrients, it has a modulating role for element translocation and plant uptake, but also fosters microbial

communities. Moreover, biochar-blended substrates had larger C contents, and this could have influenced the outcome of the PCA, especially for the CG substrates.

Considering TE retention, nutrient dynamics, plant uptake, and leaching behaviour over the course of the study, the CSK+BC substrate demonstrated a more balanced performance, in which biochar demonstrated to enhance nutrient retention over time. Indeed, CSK+BC had the lowest measured SI_PD index, indicative of minimal total concentration of potentially dangerous elements, lower translocation of Cd and Pb to plant biomass, and moderate elemental leaching to drainage water.

3.3. Potential atmospheric deposition risks

While most crop elements are absorbed from the growing media, atmospheric deposition, especially in urban environments, can also contribute to the total content found in unwashed plants (Engel-Di Mauro, 2021). This phenomenon exhibits a significant variation in response to different climatic conditions. In Mediterranean climates, which are defined by distinct wet and dry seasons, deposition patterns demonstrate seasonal variability. During the dry season, elevated atmospheric concentrations of elements result in increased deposition when precipitation occurs (Remoudaki et al., 1991).

In this sense, the comparison with commercial lettuces and the washing experiment conducted allowed us to assess both the impact of atmospheric deposition as a source of PD elements and the micronutrients composition in the leafy vegetables cultivated in rooftop agriculture compared to conventionally grown plants. Commercial and urban lettuces both had ~ 76 % C content although commercial lettuce had higher N (7.3 % vs. 4.6 %) and Na (1.1 % vs. 0.35 %), but lower Ca (1.1 % vs. 2.7 %). Among the micronutrients, key elements in commercial lettuce vs. urban lettuce were Mg (0.46 % vs. 0.69 %), Al (0.008 % vs. 0.27 %) and Fe (0.015 % vs. 0.29 %). Additionally, a broader range and diversity of micronutrients was observed in the urban lettuce (Figure S5).

Results suggested atmospheric deposition as a potential source, though levels remained well below Spanish and EU safety limits (Commission Regulation (EU) 2023/915) being 0.1 mg/kg fresh weight (FW) for Cd and 0.3 mg/kg FW for Pb, which in dry weight would be lower than 1 and 3 mg/kg respectively (considering water content to be higher than 90 %). As previously stated, the substrates were, in fact, identified as the primary sources of Cd and Pb in this study. Washing the lettuce resulted in a significant average reduction of 37 % in Al, U, V, and Pb compared to the unwashed lettuce (Fig. 6, $p < 0.05$). A moderate

reduction of 15 % was also observed for Co. The concentrations of Hg were slightly higher in the water-washed samples, which might be attributed to the variability of these elements in the samples and/or their concentrations being close to the detection limit of the equipment. In the case of Cd, lettuce before and after washing did not exhibit significant content differences, suggesting atmospheric deposition to be a negligible source of this element. Overall, the results showed that atmospheric deposition did not constitute a threat to agricultural safety at the location selected for the rooftop farming experiment. This location could provide lettuces as safe as conventionally grown and commercially available counterparts, with a broader range of micronutrients.

4. Conclusions

This study reinforces the potential of compost-based substrates as sustainable alternatives to peat, offering higher macronutrient levels without increasing trace element accumulation in edible plant parts. Tomato, lettuce, and Swiss chard grown in these substrates complied with Spanish and European Union safety standards for Cd and Pb, confirming their suitability for local food production. Atmospheric deposition in central Madrid was detected, but it was not a concerning source of contamination, and simple practices such as washing lettuce further reduced health risks.

Among the feedstock materials, agrifood byproducts—especially CSK—showed a favorable safety profile compared to other residues like seaweed. However, nutrient depletion, particularly of P and K, was observed over three years. Incorporating biochar into compost improved nutrient retention and substrate stability, highlighting its value in nutrient management and in reducing potential losses to urban water drainage systems.

Future efforts should focus on optimizing substrate formulations by exploring interactions between other locally available biowastes and biochar types to improve nutrient cycling, reduce contamination risks, and support urban circular economy goals. Overall, these findings support the integration of sustainable substrate strategies into urban agriculture, contributing to pollution mitigation, food security, and resilient urban landscapes through green infrastructure and rooftop farming.

CRedit authorship contribution statement

Giuseppe Picca: Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Marco Panettieri:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Eduardo Moreno-Jiménez:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **Medina Veliu:** Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Hugo López-Romano:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Denis Courtier-Murias:** Writing – review & editing, Validation, Supervision. **Johnny Gasperi:** Writing – review & editing, Validation. **Liliane Jean-Soro:** Writing – review & editing, Validation. **L. de Sosa Laura:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Investigation, Data curation, Conceptualization.

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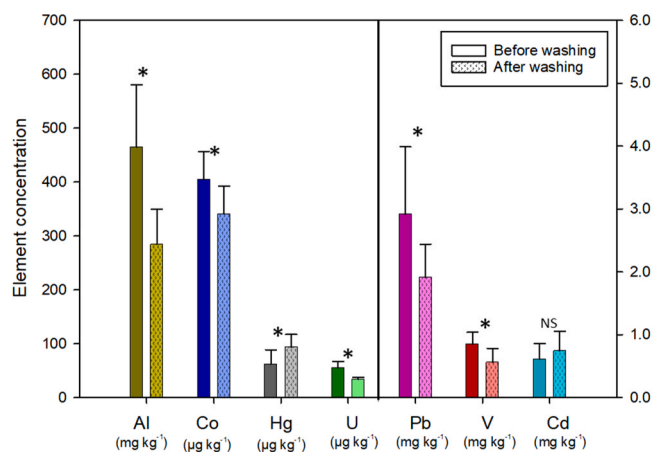


Fig. 6. Variation in dry weight concentration of selected elements in winter lettuce before (unwashed) and after washing (washed) during the 2021/22 and 2022/23 seasons, based on the Mann-Whitney *U* test. Asterisks indicate significant differences ($p < 0.05$) due to washing. NS: not significant.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ecoenv.2025.118663](https://doi.org/10.1016/j.ecoenv.2025.118663).

Data availability

Data will be made available on request.

References

- Ahmad, M., Lee, S.S., Lee, S.E., Al-Wabel, M.I., Tsang, D.C., Ok, Y.S., 2017. Biochar-induced changes in soil properties affected immobilization/mobilization of metals/metalloids in contaminated soils. *J. Soils Sediment.* 17, 717–730. <https://doi.org/10.1007/s11368-015-1339-4>.
- Alkharabsheh, H.M., Seleiman, M.F., Battaglia, M.L., Shami, A., Jalal, R.S., Alhammad, B. A., Almutairi, K.F., Al-Saif, A.M., 2021. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: a review. *Agronomy* 11, 993. <https://doi.org/10.3390/agronomy11050993>.
- Appolloni, E., Orsini, F., Specht, K., Thomaier, S., Sanyé-Mengual, E., Pennisi, G., Gianquinto, G., 2021. The global rise of urban rooftop agriculture: a review of worldwide cases. *J. Clean. Prod.* 296, 126556. <https://doi.org/10.1016/j.jclepro.2021.126556>.
- Augustsson, A., Lundgren, M., Qvarforth, A., Engström, E., Paulukat, C., Rodushkin, I., Moreno-Jiménez, E., Beesley, L., Trakal, L., Hough, R.L., 2023. Urban vegetable contamination - the role of adhering particles and their significance for human exposure. *Sci. Total Environ.* 900, 165633. <https://doi.org/10.1016/j.scitotenv.2023.165633>.
- Barrow, N.J., Hartemink, A.E., 2023. The effects of pH on nutrient availability depend on both soils and plants. *Plant Soil* 487, 21–37. <https://doi.org/10.1007/s11104-023-05960-5>.
- Bialik, O.M., Jarochovska, E., Grossowicz, M., 2021. Ordination analysis in sedimentology, geochemistry and palaeoenvironment—background, current trends and recommendations. *Depos. Rec.* 7, 541–563. <https://doi.org/10.1002/dep2.161>.
- Cambardella, C.A., Richard, T.L., Russell, A., 2003. Compost mineralization in soil as a function of composting process conditions. *Eur. J. Soil Biol.* 39, 117–127. [https://doi.org/10.1016/S1164-5563\(03\)00027-X](https://doi.org/10.1016/S1164-5563(03)00027-X).
- Clough, T.J., Condron, L.M., 2010. Biochar and the nitrogen cycle: introduction. *J. Environ. Qual.* 39, 1218–1223. <https://doi.org/10.2134/jeq2010.0204>.
- Cobb, G.P., Sands, K., Waters, M., Wixson, B.G., Dorward-King, E., 2000. Accumulation of heavy metals by vegetables grown in mine wastes. *Environ. Toxicol. Chem.* 19, 600–607. <https://doi.org/10.1002/etc.5620190311>.
- Cole, A.J., Roberts, D.A., Garside, A.L., De Nys, R., Paul, N.A., 2016. Seaweed compost for agricultural crop production. *J. Appl. Phycol.* 28, 629–642. <https://doi.org/10.1007/s10811-015-0544-2>.
- Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. *OJ L* 119 5.5.2023, p. 103.
- Conz, R., Abbruzzini, T.F., De Andrade, C.A., P. Milori, D.M.B., E. P. Cerri, C., 2017. Effect of pyrolysis temperature and feedstock type on agricultural properties and stability of biochars. *AS* 08, 914–933. <https://doi.org/10.4236/as.2017.89067>.
- Doulgeris, C., Kypritidou, Z., Kinigopoulou, V., Hatzigiannakis, E., 2023. Simulation of potassium availability in the application of biochar in agricultural soil. *Agronomy* 13, 784. <https://doi.org/10.3390/agronomy13030784>.
- Dyško, J., Kowalczyk, W., Kaniszewski, S., 2009. The influence of pH of nutrient solution on yield and nutritional status of tomato plants grown in soilless culture system. *J. Fruit. Ornament. Plant Res.* 70, 59–69. <https://doi.org/10.2478/v10032-009-0006-y>.
- EFSA, 2009. Scientific opinion on arsenic in food. *EFSA J.* 7 (10), 1351. <https://doi.org/10.2903/j.efsa.2009.1351>.
- EFSA, 2021. Tolerable upper intake levels for vitamins and minerals – update. *EFSA Support. Publ.* 18 (4), 6566E. <https://doi.org/10.2903/sp.efsa.2021.EN-6566>.
- Engel-Di Mauro, S., 2021. Atmospheric sources of trace element contamination in cultivated urban areas: a review. *J. Environ. Qual.* 50, 38–48. <https://doi.org/10.1002/jeq2.20078>.
- FAO/WHO, 2016. General Standard for Contaminants and Toxins in Food and Feed (CODEX STAN (193-1995). Available from: (https://www.fao.org/fao-who-codexalimentarius/sh-proxy/fr/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252Fstandards%252FCXS%2B193-1995%252FCXS_193e.pdf).
- Fussy, A., Papenbrock, J., 2022. An overview of soil and soilless cultivation techniques—chances, challenges and the neglected question of sustainability. *Plants* 11 (9), 1153. <https://doi.org/10.3390/plants11091153>.
- Goñi-Urtiaga, A., Courtier-Murias, D., Picca, G., Valentín, J.L., Plaza, C., Panettieri, M., 2022. Response of water-biochar interactions to physical and biochemical aging. *Chemosphere* 307, 136071. <https://doi.org/10.1016/j.chemosphere.2022.136071>.
- González Fernández, L.A., Navarro Frómota, A.E., Carranza Álvarez, C., Flores Ramírez, R., Díaz Flores, P.E., Castillo Ramos, V., Sánchez Polo, M., Carrasco Marín, F., Medellín Castillo, N.A., 2023. Valorization of sargassum biomass as potential material for the remediation of heavy-metals-contaminated waters. *IJERPH* 20, 2559. <https://doi.org/10.3390/ijerph20032559>.
- Grard, B.J.-P., Chenu, C., Manouchehri, N., Houot, S., Frascaria-Lacoste, N., Aubry, C., 2018. Rooftop farming on urban waste provides many ecosystem services. *Agron. Sustain. Dev.* 38, 2. <https://doi.org/10.1007/s13593-017-0474-2>.
- Grard, B.J.-P., Manouchehri, N., Aubry, C., Frascaria-Lacoste, N., Chenu, C., 2020. Potential of technosols created with urban by-products for rooftop edible production. *IJERPH* 17, 3210. <https://doi.org/10.3390/ijerph17093210>.
- Gupta, N., Yadav, K.K., Kumar, V., Kumar, S., Chadd, R.P., Kumar, A., 2019. Trace elements in soil-vegetables interface: translocation, bioaccumulation, toxicity and amelioration - a review. *Sci. Total Environ.* 651, 2927–2942. <https://doi.org/10.1016/j.scitotenv.2018.10.047>.
- Hagemann, N., Joseph, S., Schmidt, H.-P., Kammann, C.I., Harter, J., Borch, T., Young, R. B., Varga, K., Taherymoosavi, S., Elliott, K.W., McKenna, A., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-Alonso, A., Orsetti, S., Subdiaga, E., Behrens, S., Kappler, A., 2017. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nat. Commun.* 8, 1089. <https://doi.org/10.1038/s41467-017-01123-0>.
- Handiso, B., Pääkkönen, T., Wilson, B.P., 2024. Effect of pyrolysis temperature on the physical and chemical characteristics of pine wood biochar. *Waste Manag. Bull.* 2, 281–287. <https://doi.org/10.1016/j.wmb.2024.11.008>.
- Harada, Y., Whitlow, T.H., Russell-Anelli, J., Walter, M.T., Bassuk, N.L., Rutzke, M.A., 2019. The heavy metal budget of an urban rooftop farm. *Sci. Total Environ.* 660, 115–125. <https://doi.org/10.1016/j.scitotenv.2018.12.463>.
- Harada, Y., Whitlow, T.H., 2020. Urban rooftop agriculture: challenges to science and practice. *Front. Sustain. Food Syst.* 4. <https://doi.org/10.3389/fsufs.2020.00076>.
- Hemphill, D.D., Jackson, T.L., 1982. Effect of soil acidity and nitrogen on yield and elemental concentration of bush bean, carrot, and lettuce1. *J. Am. Soc. Hort. Sci.* 107, 740–744. <https://doi.org/10.21273/JASHS.107.5.740>.
- Izquierdo, M., De Miguel, E., Ortega, M.F., Mingot, J., 2015. Bioaccessibility of metals and human health risk assessment in community urban gardens. *Chemosphere* 135, 312–318. <https://doi.org/10.1016/j.chemosphere.2015.04.079>.
- Jean-Soro, L., Le Guern, C., Bechet, B., Lebeau, T., Ringard, M.-F., 2015. Origin of trace elements in an urban garden in Nantes, France. *J. Soils Sediment.* 15, 1802–1812. <https://doi.org/10.1007/s11368-014-0952-y>.
- Kabata-Pendias, A., 2010. Trace elements in soils and plants, 4 ed. ed. CRC Press, Boca Raton, Fla. <https://doi.org/10.1201/b10158>.
- Kabata-Pendias, A., Mukherjee, A.B., 2007. Trace Elements from Soil to Human. Springer Berlin Heidelberg, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-540-32714-1>.
- Kabata-Pendias, A., Szteke, B., 2015. Trace Elements in Abiotic and Biotic Environments, 1st ed. CRC Press, Boca Raton. <https://doi.org/10.1201/b18198>.
- Kaur, S., Kaur, N., Siddique, K.H.M., Nayyar, H., 2016. Beneficial elements for agricultural crops and their functional relevance in defence against stresses. *Arch. Agron. Soil Sci.* 62, 905–920. <https://doi.org/10.1080/03650340.2015.1101070>.
- Kicińska, A., Pomykała, R., Izquierdo-Diaz, M., 2022. Changes in soil pH and mobility of heavy metals in contaminated soils. *Eur. J. Soil Sci.* 73, e13203. <https://doi.org/10.1111/ejss.13203>.

- Kupper, T., Bürge, D., Bachmann, H.J., Gusewell, S., Mayer, J., 2014. Heavy metals in source-separated compost and digestates. *Waste Manag.* 34, 867–874. <https://doi.org/10.1016/j.wasman.2014.02.007>.
- Lal, R., 2017. *Urban Agriculture in the 21st Century*. Boca Raton: Taylor & Francis, 2017. In: Lal, R., Stewart, B.A. (Eds.), *Urban Soils*. CRC Press, Series: Advances in soil science, pp. 1–14. <https://doi.org/10.1201/9781315154251-1>. Boca Raton: Taylor & Francis, 2017.
- Lehmann, J., Joseph, S., 2024. *Biochar for Environmental Management: Science, Technology and Implementation*, 3rd ed. Routledge, London. <https://doi.org/10.4324/9781003297673>.
- Lima, C.A.I., Pestana, I.A., Azevedo, L.S., Ribeiro, D.P., Almeida, M.G., Prins, C.L., Marciano, C.R., Souza, C.M.M., 2019. Bioconcentration and translocation of Cd and Hg in a tomato (*Solanum lycopersicum*) from cultivated soils in southeastern Brazil. *Environ. Monit. Assess.* 191, 103. <https://doi.org/10.1007/s10661-019-7242-5>.
- Madejón, P., Barba-Brioso, C., Lepp, N.W., Fernández-Caliani, J.C., 2011. Traditional agricultural practices enable sustainable remediation of highly polluted soils in Southern Spain for cultivation of food crops. *J. Environ. Manag.* 92, 1828–1836. <https://doi.org/10.1016/j.jenvman.2011.03.007>.
- Madejón, E., Panettieri, M., Madejón, P., Pérez-de-Mora, A., 2021. Composting as sustainable valor option for seaweed blooms on recreational beaches. *Waste Biomass. Valor* 13, 863–875. <https://doi.org/10.1007/s12649-021-01548-1>.
- Mazzatorta, P., Benfenati, E., Neagu, D., Gini, G., 2002. The importance of scaling in data mining for toxicity prediction. *J. Chem. Inf. Comput. Sci.* 42, 1250–1255. <https://doi.org/10.1021/ci025520n>.
- Mazziotta, M., Pareto, A., 2022. Normalization methods for spatio-temporal analysis of environmental performance: revisiting the Min–Max method. *Environmetrics* 33 (5), e2730. <https://doi.org/10.1002/env.2730>.
- McLaughlin, M.J., Smolders, E., Degryse, F., Rietra, R., 2011. Uptake of Metals from Soil into Vegetables. In: Swartjes, F.A. (Ed.), *Dealing with Contaminated Sites*. Springer Netherlands, Dordrecht, pp. 325–367. https://doi.org/10.1007/978-90-481-9757-6_8.
- Natasha, I., Bibi, I., Niazi, N.K., Shahid, M., Ali, F., Hasan, I.M., ul, Rahman, M.M., Younas, F., Hussain, M.M., Mehmood, T., Shaheen, S.M., Naidu, R., Rinklebe, J., 2022. Distribution and ecological risk assessment of trace elements in the paddy soil–rice ecosystem of Punjab, Pakistan. *Environ. Pollut.* 307, 119492. <https://doi.org/10.1016/j.envpol.2022.119492>.
- Nordbeck, R., Hög, K., 2024. National peatland strategies in Europe: current status, key themes, and challenges. *Reg. Environ. Change* 24, 5. <https://doi.org/10.1007/s10113-023-02166-4>.
- Park, W., Kim, H., Park, H., Choi, S., Hong, S.J., Bahk, Y.-M., 2021. Biochar as a low-cost, eco-friendly, and electrically conductive material for terahertz applications. *Sci. Rep.* 11, 18498. <https://doi.org/10.1038/s41598-021-98009-5>.
- Picca, G., Goñi-Urtiaga, A., de Sosa, L.L., Rodriguez, M.V.C., Navarro, I.F., Plaza, C., Panettieri, M., 2025. Sustainability in urban agriculture: the role of biochar in enhancing the productive capacity of compost-based growing media for rooftop farming. *Urban For. Urban Green.* 107, 128774. <https://doi.org/10.1016/j.ufug.2025.128774>.
- Picca, G., Plaza, C., Madejón, E., et al., 2023. Compositing of coffee silverskin with carbon rich materials leads to high quality soil amendments. *Waste Biomass. Valor* 14, 297–307. <https://doi.org/10.1007/s12649-022-01879-7>.
- Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A.R., Lehmann, J., 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biol. Fertil. Soils* 48, 271–284. <https://doi.org/10.1007/s00374-011-0624-7>.
- Rashmi, I., Shirale, A., Kartikha, K.S., Shinogi, K.C., Meena, B.P., Kala, S., 2017. Leaching of Plant Nutrients from Agricultural Lands. In: Naeem, M., Ansari, A.A., Gill, S.S. (Eds.), *Essential Plant Nutrients*. Springer International Publishing, Cham, pp. 465–489. https://doi.org/10.1007/978-3-319-58841-4_19.
- Remoudaki, E., Bergametti, G., Buat-Ménard, P., 1991. Temporal variability of atmospheric lead concentrations and fluxes over the northwestern Mediterranean Sea. *J. Geophys. Res. Atmos.* 96 (D1), 1043–1055. <https://doi.org/10.1029/90JD00111>.
- Sánchez-Monedero, M.A., Sánchez-García, M., Castejón-del Pino, R., Fornes, F., Belda, R. M., Lidón, A., Cayuela, M.L., 2021. Biochar as an additive in composting: impact on process performance and on the agronomical quality of the end product. *Acta Hort.* 175–188. <https://doi.org/10.17660/ActaHortic.2021.1317.21>.
- Schmidt, H., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sánchez Monedero, M.A., Cayuela, M.L., 2021. Biochar in agriculture – a systematic review of 26 global meta-analyses. *GCB Bioenergy* 13, 1708–1730. <https://doi.org/10.1111/gcbb.12889>.
- Singh, A., Sharma, R.K., Agrawal, M., Marshall, F.M., 2010. Risk assessment of heavy metal toxicity through contaminated vegetables from waste water irrigated area of Varanasi, India. *Trop. Ecol.* 51, 375–387.
- Smith, J.S., Winston, R.J., Tirpak, R.A., Wituszynski, D.M., Boening, K.M., Martin, J.F., 2020. The seasonality of nutrients and sediment in residential stormwater runoff: implications for nutrient-sensitive waters. *J. Environ. Manag.* 276, 111248. <https://doi.org/10.1016/j.jenvman.2020.111248>.
- Sparks, D.L., 2003. *Environmental Soil Chemistry*. Academic Press. <https://doi.org/10.1016/B978-012656446-4/50001-3>.
- Sun, Z., Hu, Y., Shi, L., Li, G., Pang, Z., Liu, S., Chen, Y., Jia, B., 2022. Effects of biochar on soil chemical properties: a global meta-analysis of agricultural soil. *Plant Soil Environ.* 68, 272–289. <https://doi.org/10.17221/522/2021-PSE>.
- Theodorou, P., Radzevičiūtė, R., Lentendu, G., Kahnt, B., Husemann, M., Bleidorn, C., Settele, J., Schweiger, O., Grosse, I., Wubet, T., Murray, T.E., Paxton, R.J., 2020. Urban areas as hotspots for bees and pollination but not a panacea for all insects. *Nat. Commun.* 11, 576. <https://doi.org/10.1038/s41467-020-14496-6>.
- Vasheghian, Y., Nadagouda, M.M., Aminabhavi, T.M., 2024. Biochar-enhanced bioremediation of eutrophic waters impacted by algal blooms. *J. Environ. Manag.* 367, 122044. <https://doi.org/10.1016/j.jenvman.2024.122044>.
- Walters, S.A., Stoelzle Midden, K., 2018. Sustainability of urban agriculture: vegetable production on green roofs. *Agriculture* 8, 168. <https://doi.org/10.3390/agriculture8110168>.
- Wang, L., O'Connor, D., Rinklebe, J., Ok, Y.S., Tsang, D.C.W., Shen, Z., Hou, D., 2020. Biochar aging: mechanisms, physicochemical changes, assessment, and implications for field applications. *Environ. Sci. Technol.* 54, 14797–14814. <https://doi.org/10.1021/acs.est.0c04033>.
- Wielemaker, R., Oenema, O., Zeeman, G., Weijma, J., 2019. Fertile cities: nutrient management practices in urban agriculture. *Sci. Total Environ.* 668, 1277–1288. <https://doi.org/10.1016/j.scitotenv.2019.02.424>.
- Woldeamanuel, A.A., Tarekegn, M.M., Balakrishna, R.M., 2022. *Prod. Appl. Org. Waste Compost Urban Agric. Emerg. Cities* 16.
- Zhou, H., Yang, W.-T., Zhou, X., Liu, L., Gu, J.-F., Wang, W.-L., Zou, J.-L., Tian, T., Peng, P.-Q., Liao, B.-H., 2016. Accumulation of heavy metals in vegetable species planted in contaminated soils and the health risk assessment. *IJERPH* 13, 289. <https://doi.org/10.3390/ijerph13030289>.
- Ziss, E., Friesl-Hanl, W., Göttinger, S., Noller, C., Puschenreiter, M., Watzinger, A., Hood-Nowotny, R., 2021. Exploring the potential risk of heavy metal pollution of edible cultivated plants in urban gardening contexts using a citizen science approach in the project “heavy metal city-zen. *Sustainability* 13, 8626. <https://doi.org/10.3390/su13158626>.