agronomy

MDPI

Article

Application of Compost as an Organic Amendment for Enhancing Soil Quality and Sweet Basil (*Ocimum basilicum* L.) Growth: Agronomic and Ecotoxicological Evaluation

Majda Oueld Lhaj [1,2,*], Rachid Moussadek [3], Latifa Mouhir [1], Hatim Sanad [1,2], Khadija Manhou [2,4], Oumaima Iben Halima [2], Hasna Yachou [2], Abdelmjid Zouahri [2] and Meriem Mdarhri Alaoui [2]

[1] Laboratory of Process Engineering and Environment, Faculty of Science and Technology Mohammedia, University Hassan II of Casablanca, Mohammedia 28806, Morocco; latifa.mouhir@fstm.ac.ma (L.M.); hatim.sanad-etu@etu.univh2c.ma (H.S.)
[2] Research Unit on Environment and Conservation of Natural Resources, Regional Center of Rabat, National Institute of Agricultural Research, AV. Ennasr, Rabat 10101, Morocco; khadija.manhou@uit.ac.ma (K.M.); oumaima.ibenhalima@inra.ma (O.I.H.); hasna.yachou@inra.ma (H.Y.); abdelmjid.zouahri@inra.ma (A.Z.); meriem.alaouimdarhri@inra.ma (M.M.A.)
[3] International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat 10100, Morocco; r.moussadek@cgiar.org
[4] Laboratory of Natural Resources and Sustainable Development, Department of Biology, Faculty of Sciences, Ibn Tofail University, Kenitra 14000, Morocco
* Correspondence: majda.oueldlhaj-etu@etu.univh2c.ma

Abstract: This study investigates the effectiveness of organic compost as a sustainable alternative to chemical fertilizers for improving soil health and enhancing crop productivity under greenhouse conditions. The experiment focused on sweet basil (*Ocimum basilicum* L.), an aromatic herb highly sensitive to soil fertility and structure, cultivated in sandy loam soil—a prevalent substrate in arid and semi-arid regions, often limited by poor water and nutrient retention. Using a randomized complete block design with six compost application rates, this study evaluated the physicochemical, biochemical, and agronomic responses of both soil and plants. The results demonstrated significant improvements across all parameters ($p < 0.05$), with the 30 t/ha compost treatment yielding the most notable enhancements in soil structure, nutrient content, and plant performance while maintaining acceptable levels of heavy metals. Soil organic matter (SOM) increased to 13.71%, while shoot length (SL), essential oil content (EOC), and the 100-seed weight improved to 42 cm, 0.83%, and 0.32 g, respectively, compared to the control. These finding underscore the benefits of high compost application rates in boosting greenhouse horticultural productivity while promoting sustainable agriculture. Moreover, this study supports the reduction in chemical fertilizer dependency and encourages the adoption of circular economy principles (CEPs) through organic waste recycling.

Keywords: compost; sandy soil; sweet basil; organic amendment; sustainable agronomy; soil fertility

check for updates

Academic Editor: Guang-Wei Ding

Received: 25 March 2025
Revised: 19 April 2025
Accepted: 24 April 2025
Published: 26 April 2025

Citation: Oueld Lhaj, M.; Moussadek, R.; Mouhir, L.; Sanad, H.; Manhou, K.; Iben Halima, O.; Yachou, H.; Zouahri, A.; Mdarhri Alaoui, M. Application of Compost as an Organic Amendment for Enhancing Soil Quality and Sweet Basil (*Ocimum basilicum* L.) Growth: Agronomic and Ecotoxicological Evaluation. *Agronomy* **2025**, *15*, 1045. https://doi.org/10.3390/agronomy15051045

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In agriculture, soil serves as the principal reservoir for nutrients essential to plant growth and sustainable crop production [1]. Soil fertility, a key indicator of this nutrient richness, is influenced by the balance between nutrient inputs and outputs within the soil ecosystem [2]. In arid regions, the balance of soil nutrients is particularly vulnerable to a range of climatic and anthropogenic factors [3]. Over-reliance on chemical and synthetic

fertilizers, frequent soil tillage, irrational agricultural practices, entrenched social habits, and extreme climate conditions such as high temperatures and minimal precipitation significantly contribute to soil infertility and the degradation of SOM [4–6]. The decline in SOM severely impairs critical soil attributes, including physical structure, aggregate stability, water-holding capacity (WHC), gas flux, plant root growth, nutrient balance, and microbial activity [7]. This degradation not only affects the soil quality but also exacerbates climate change, as agriculture contributes approximately 10–12% of global greenhouse gas emissions (GHGs) [8]. Consequently, these negative impacts often lead to reduced plant growth and lower crop yields [9].

Soil quality degradation is a pressing global issue, particularly in semi-arid Mediterranean regions, where the challenges are more pronounced [10]. Enhancing and maintaining soil fertility through eco-friendly management strategies is crucial for sustaining soil health and supporting crop production systems, especially in arid conditions characterized by sandy soils [11]. These soils present significant agricultural challenges due to their low fertility, limited WHC, high infiltration rate (IR), and high evapotranspiration [12]. Numerous efforts, including the application of both organic and inorganic amendments, have been made to improve the characteristics of sandy soils [13].

Sandy loam soils are widely utilized in agriculture due to their favorable drainage and aeration properties, which facilitate root development and ease of cultivation [14]. However, these soils often present challenges such as low SOM and poor water and nutrient retention capacities [15]. These limitations can lead to reduced soil fertility and necessitate frequent irrigation and fertilization to sustain crop productivity. Studies have demonstrated that organic amendments (OAs), such as compost, have a positive impact on sandy soils in arid and semi-arid conditions [16]. Composting is a widely used method for treating organic waste, producing a humus-like material that serves as an OA [17]. Compost enhances SOM levels and increases the availability of nutrients, promoting plant growth and stimulating beneficial soil microorganisms without the accumulation of harmful chemical residues, leading to certified organic products [18,19]. Additionally, composting helps reduce organic carbon mineralization and promotes carbon sequestration (CS) in the soil, while also immobilizing heavy metals [20]. Consequently, many farmers increasingly use various types of compost with a minimal inorganic fertilizer application to maintain soil fertility [21]. This approach can reduce costs by up to 18% compared to the use of inorganic amendments [22]. Composting has long been an effective method for organic waste management, involving specific aerobic conditions where factors such as moisture content, airflow, temperature, and carbon-to-nitrogen (C/N) ratio are crucial for optimal microbial performance [23]. Integrating OAs not only improves the physical, chemical, and biological properties of soil but also minimizes the use of synthetic amendments, which significantly enhances fertility, conserves and recycles energy, reduces pollution, and lowers costs for farmers, especially in low-income countries facing arid and semi-arid conditions [24].

Sweet basil (*Ocimum basilicum* L.), a member of the Lamiaceae family, is a versatile and highly valued herb known for its ornamental, aromatic, and medicinal properties [25]. Native to the tropical regions of Southern Asia, basil has adapted remarkably well to diverse ecological conditions, enabling its widespread cultivation around the globe, including in the Mediterranean basin [22]. Its adaptability and high ecological plasticity make it a staple in various climates [26]. Basil is not just a culinary delight but also has medicinal properties [27]. It is widely recognized for its antioxidant, antimicrobial, and insecticidal potential, which contribute to its use in the food, pharmaceutical, and perfume industries [28]. Despite its robustness, basil is sensitive to both water stress and soil fertility levels. Water stress can adversely affect basil's growth, reducing its yield and overall plant

health [29]. Proper irrigation practices are thus crucial to ensure the plant's vitality and productivity, especially in regions prone to drought or erratic rainfall [30].

Nutrient management is another critical factor influencing basil's growth. Studies have shown that excessive nitrogen fertilization, such as applications of 500 mg N/L, can reduce basil's leaf area, possibly due to nutrient imbalances or toxicity [31]. On the other hand, the application of compost has been found to significantly enhance basil's yield [32]. OAs like compost not only improve soil structure and fertility but also provide a more balanced nutrient supply, supporting the plant's growth [33]. The application of compost has demonstrated profound benefits in basil cultivation [34]. Higher compost rates correlate with greater yields, likely due to the improved soil conditions and nutrient availability that compost provides [8]. Composting not only enriches the soil with essential nutrients but also creates an optimal growing environment for basil [35].

In the context of sustainable agriculture, the use of compost as an OA aligns with the principles of eco-friendly farming [36]. It reduces reliance on chemical fertilizers, promotes soil health, and supports sustainable crop production systems [33]. This is particularly beneficial in regions with a poor soil fertility or harsh climatic conditions, where maintaining soil health is crucial for long-term agricultural productivity [37]. Furthermore, sustainable basil cultivation using OAs like compost contributes to environmental stewardship [38]. It minimizes the environmental footprint of agriculture by reducing GHGs and preventing nutrient runoff into waterways [39]. Moreover, the integration of OAs aligns with CEPs, which prioritize waste reduction, material recycling, and resource reutilization to establish a more sustainable agricultural system.

This experiment aims to assess the effects of the application of organic compost on sandy soil cultivated with basil plants. The specific research objectives are as follows: (1) to analyze how different application rates of compost affect the soil's physical and chemical properties; (2) to evaluate changes in the agronomic, morphological, physiological, and biochemical characteristics of basil plants under various treatments; (3) to evaluate the ecotoxicological impact of trace elements on soil and sweet basil, assessing their accumulation and potential transfer within the soil–plant system; (4) to employ multivariate statistical analyses, including ANOVA, PCA, and Pearson's correlation, to reveal the interactions between all the involved parameters; and (5) to provide practical recommendations for substituting chemical amendment with organic alternatives.

2. Materials and Methods

2.1. Setup and Soil Description

The experiment was conducted in the greenhouse station of the Environment Unit at the National Institute of Agronomic Research (INRA) in Rabat, Morocco. The soil utilized for this study was sourced from Tiflet, an area known for its barren land, untouched by cultivation for over a decade due to its low fertility (Figure 1). The collected soil samples underwent thorough laboratory analysis to assess their physical and chemical properties. Initially, the soil was air-dried and passed through a 2 mm sieve for physical analysis and further through a 0.25 mm sieve for chemical analysis. The experiments were conducted between February and August 2024, including both greenhouse trials and laboratory analyses.

In terms of textural composition, the soil from Tiflet consisted of 57.9% sand, 27.24% silt, and 14.86% clay, categorizing it as a sandy loam soil according to the USDA textural classification system [40]. The soil texture was precisely determined using the hydrometer method [41]. Additionally, the soil contained 2.95% of total $CaCO_3$, as determined by the Collins calcimeter method [2], with a pH of 7.3 and an electrical conductivity (EC) of 201 µS/cm.

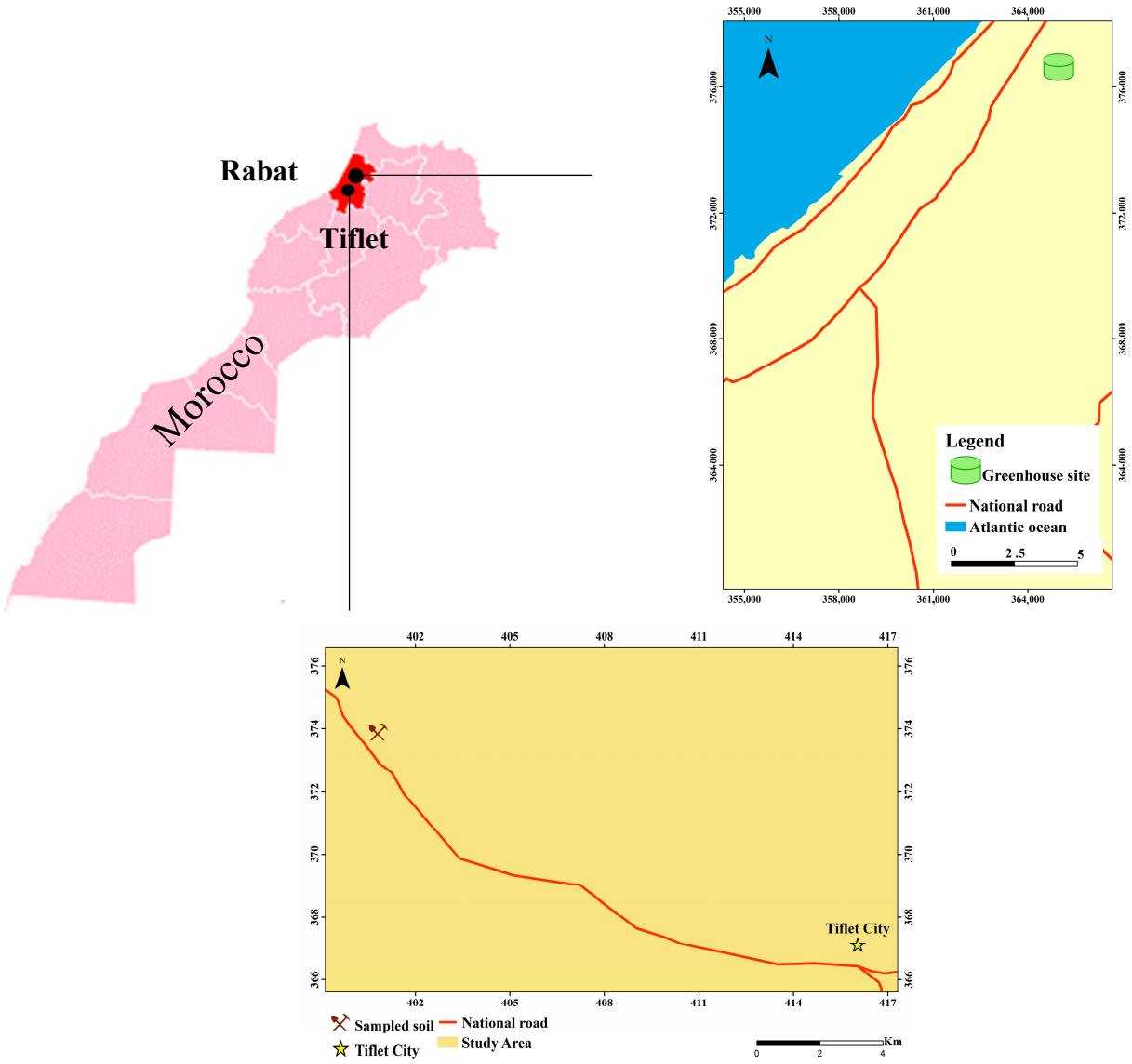


Figure 1. Geographical distribution of sampling and experimental areas for our study.

2.2. Experimental Design and Treatment

The experiment was conducted under controlled greenhouse conditions at INRA in Rabat, Morocco, where the temperature were maintained at approximately 23 ± 2.5 °C, and relative humidity was stabilized at around 62 ± 8%. To ensure uniform environmental conditions and reduce the influence of external weather fluctuations, the greenhouse was equipped with horizontal airflow fans and automated shading systems. Each pot, measuring 20 cm in height and 15 cm in diameter, was filled with approximately 3 kg of soil following the designated treatment plan. The experimental design included six different treatments:

- T1: Negative control (sandy loam soil only);
- T2: Sandy loam soil + 10 t/ha organic compost;
- T3: Sandy loam soil + 20 t/ha organic compost;
- T4: Sandy loam soil + 30 t/ha organic compost;
- T5: Sandy loam soil + 40 t/ha organic compost;
- T6: Positive control (Sandy loam soil mix with granular chemical fertilizer NPK (20.10.10) at rate of 250 kg/ha)

All treatments were applied in a completely randomized manner to ensure experimental validity and reliability. Each treatment was replicated four times, and each pot was sown with five seeds of basil. The chemical fertilizer was applied in a single dose at the transplanting time, ensuring uniform distribution across all the treatment's repetitions. The culture was cultivated under natural light conditions, and without the application of any synthetic fertilizers. All pots received the same amount of water throughout the experiment, following a standardized irrigation schedule. Two weeks prior to sowing, the various compost treatments were manually mixed into the topsoil of each pot to ensure thorough integration. The basil seeds were planted at a depth of approximately 2 cm below the soil surface in each pot, and a thinning procedure was subsequently implemented to ensure a uniform plant density. Initial soil samples were collected immediately after the compost application to characterize the initial soil properties. Following a 90-day growth period, which represented a full crop cycle for the basil, final soil samples were taken to assess the changes in soil properties due to the different compost treatments.

2.3. Compost Preparation and Chemical Characterization

In this study, the compost utilized was prepared following the established procedures outlined in [42]. The composting process took place at the botanic garden of INRA in Rabat. This involved the co-composting of a mixture of green wastes, predominantly leaves, along with organic sheep manure over a 120-day period. Throughout this duration, the composting occurred under carefully controlled aerobic conditions to ensure optimal decomposition and nutrient retention. The green waste provided a rich source of carbon, while the manure supplied essential nitrogen, creating a balanced feedstock that supported microbial activity and OM breakdown. This composting process ensured the generation of a high-quality OA, with its main physical and chemical characteristics presented in Table 1.

Table 1. Physical and chemical characteristics of the organic compost.

				Compost				
Parameters	**pH**	**CE**	**OM**	**N**	**P**	**K**	**WHC**	**C/N**
Unit	-	mS/cm	%DM	%DM	%DM	%DM	%	-
Compost	6.8	2.92	29	1.98	3.22	0.61	122	16.15
				Compost				
Parameters	**Zn**	**Cu**	**Fe**	**Mn**	**Cd**	**Pb**	**Ni**	**As**
Unit	mg/kg DM	mg/kg DM	mg/kg DM	mg/kg DM	mg/kg DM	mg/kg DM	mg/kg DM	mg/kg DM
Compost	83	ND	321	230	ND	ND	ND	ND

ND: non-detected, (Fe) iron, (Cu) copper, (Zn) zinc, (Mn) manganese, (Cd) cadmium, (Pb) lead, (Ni) nickel, (As) arsenic.

2.4. Soil Physical and Chemical Measurement

Before sowing and after harvesting, various physical and chemical properties of the soil were thoroughly assessed using the standard procedures [43]. Soil samples were collected from two points in each pot and combined to create a homogeneous composite sample. These samples underwent preparation before analysis to ensure accurate measurements. All the measurements represented the average values from four experimental repetitions.

Soil pH and EC were determined in an aqueous solution with a 1:2 (w/v), as described by Yeon Kim et Ju Lee [44]. Measurements were taken using a pH meter (Mettler Toledo Seven Easy-728 Metrohm) and a conductivity meter (Orion model 162). The SOM content was assessed using the Walkley–Black method [45], where the sample was oxidized with potassium dichromate and concentrated sulfuric acid and titered with ferrous ammonium

sulfate until a color changed. The soil organic carbon (SOC) was measured through a modified wet combustion method [46]. The available nitrogen (Av. N), exchangeable potassium (Ex. K), available phosphorus (Av. P), calcium (Ca), magnesium (Mg), and the cation exchange capacity (CEC) were also analyzed according to the methods used by Sanad et al. [2].

In addition to chemical properties, several physical properties of the soil were assessed. These included WHC, IR, bulk density (BD), total porosity (TP), water retention capacity (WRC), and particle size distribution (PDS).

WHC was determined by saturating soil samples with water and then calculating the retained water as a percentage of the soil's dry weight, using the following formula [47]:

$$\text{WHC} = \frac{\text{Weight of wet soil}}{\text{Weight of dry soil}} \times 100 \quad (1)$$

IR was measured using the double-ring infiltrometer technique and calculated with the following formula [48]:

$$\text{IR} = \frac{1}{2} \times \left(\text{S} \times \text{t}^{-\frac{1}{2}}\right) + \text{A} \quad (2)$$

where S is the sample's sorptivity (m/s^2), t is time (s), and A is water transmissivity (m/s).

BD was determined using a cylindrical, sharp-edged core sample, calculated as [49]:

$$\text{BD} = \frac{\text{Dry weight of the sample}}{\text{Volume of the sample}} \times 100 \quad (3)$$

TP indicates the volume of soil pores and was calculated by the formula [50]:

$$\text{TP} = \frac{(\text{Weight of soil at saturation} - \text{Soil dry weight})}{\text{Volume of the sample}} \times 100 \quad (4)$$

WRC was assessed by saturating the sample with water and measuring the volume of drained water [51]. PDS was determined using a sieve analysis method with sieves of varying dimensions (3 mm, 2 mm, 1 mm, and 0.25 mm), weighing each particle size fraction to understand the soil's textural composition [52].

2.5. Plant Physiological, Agronomic, and Biochemical Attributes

At the end of the plant growth, several key attributes of the plants were meticulously recorded. Flower count per plant (NF) was noted at the full flowering stage, and the average was documented. Post-harvest, the shoot, roots, leaves, and seeds were separated for detailed analysis.

For each shoot, we measured parameters including shoot fresh weight (SFW), shoot dry weight (SDW), number of leaves (NL), SL, number of branches (NB), and the number of yellow leaves (NYL). Any leaves under 1 cm and cotyledons were excluded. Nutrient content was determined for the seeds (Av. N, P, and K) [43], and the weight of 100 seeds was recorded. During the vegetative stage, intermediate leaves underwent a comprehensive assessment, where parameters such as the membrane stability index (MSI) were measured following the protocol in [53]. The average leaf length (ALL), leaf width (ALW), and leaf area (ALA) were measured per shoot in each pot [20]. The water content (WC), representing the plant's tissue hydration, was calculated using the fresh weight (FW) and dry weight (DW) with the following formula [51]:

$$\text{WC} = \frac{(\text{FW} - \text{DW})}{\text{DW}} \quad (5)$$

The relative water content (RWC), a crucial physiological indicator of the plant's water status, was assessed by first determining the fresh weight (FW), followed by saturating the leaves for 12 h in distilled water. After saturation, the leaves were wiped and weighed to obtain the saturation weight (SW). The leaves were then oven-dried at 60 °C for 72 h to obtain the dry weight (DW). RWC was calculated using Equation (6) [54]:

$$\mathrm{RWC} = \frac{(\mathrm{FW} - \mathrm{DW})}{(\mathrm{SW} - \mathrm{DW})} \times 100 \quad (6)$$

The total chlorophyll content (TCC) CCI units were assessed using a portable chlorophyll content meter (CCM-200 plus non-destructive, Opti-Sciences, ADC BioScientificLtd., Hoddesdon, Hertfordshire, UK) the day before harvest, using randomly selected, fully developed leaves. Chlorophyll a and b were extracted using the method described by Cabanillas et al. [8], employing a UV–visible spectrophotometer (JENWAY 6405 Model) on three randomly selected mature fresh leaves [19,53]. The EOC of the plant was extracted from the fresh shoot through steam distillation for 3 h, as described by Perbellini et al. [55].

At the end of the flowering stage, the roots were carefully washed with water and dried with a paper to remove excess moisture. The primary root length (PRL) was measured in centimeters, and the root fresh weight (RFW) was recorded before drying the roots in an oven at 65 °C until a constant weight was achieved to determine the root dry weight (RDW).

2.6. Accumulation of Heavy Metals in Soil and Plant Tissues

Heavy metal (HM) concentrations in both soil and plant samples were quantified using Atomic Absorption Spectrophotometry (AAS), following standardized acid digestion procedures as outlined by [56,57]. Soil samples underwent digestion with aqua regia (a 3:1 mixture of HCl and HNO_3), whereas plant tissues were processed using a combination of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). The digested extracts were subsequently analyzed for essential and toxic metals, including Fe, Cu, Zn, Mn, Cd, Pb, Ni, and As, using a properly calibrated AAS system.

The Accumulation Coefficient Factor (ACF) is calculated as the ratio of the metal content in the entire plant (PU) (typically on a dry mass basis) to the total metal content in the soil (MT). The ACF was calculated using Equation (7) [58]:

$$\mathrm{ACF} = \frac{\mathrm{PU}}{\mathrm{MT}} \quad (7)$$

2.7. Multivariate Statistical Analysis (MSA)

The data obtained for various soil properties and final plant properties from each treatment were subjected to a statistical analysis of variance (ANOVA) using IBM SPSS Statistics 25, to assess the effects of different treatments on the soil's physical and chemical properties and plant growth. The results were expressed as mean values of four replicate samples, providing a robust and reliable dataset for evaluating the impact of each treatment on soil and plant parameters. To identify associations between soil properties and plant yield, the Pearson correlation procedure ($p < 0.05$) was performed, establishing significant correlations [59]. Principal component analysis (PCA) was also conducted to classify a large number of variables into major components and to reduce the data dimensionality while retaining the most significant variations along all the treatments. The PCA aimed to investigate the influences of different treatments on soil properties and plant growth. These analyses aimed to determine correlations and interactions between different inputs, providing a comprehensive understanding of the treatment effects on both soil and plant parameters.

The flow-sheet of our study is represented in Figure 2.

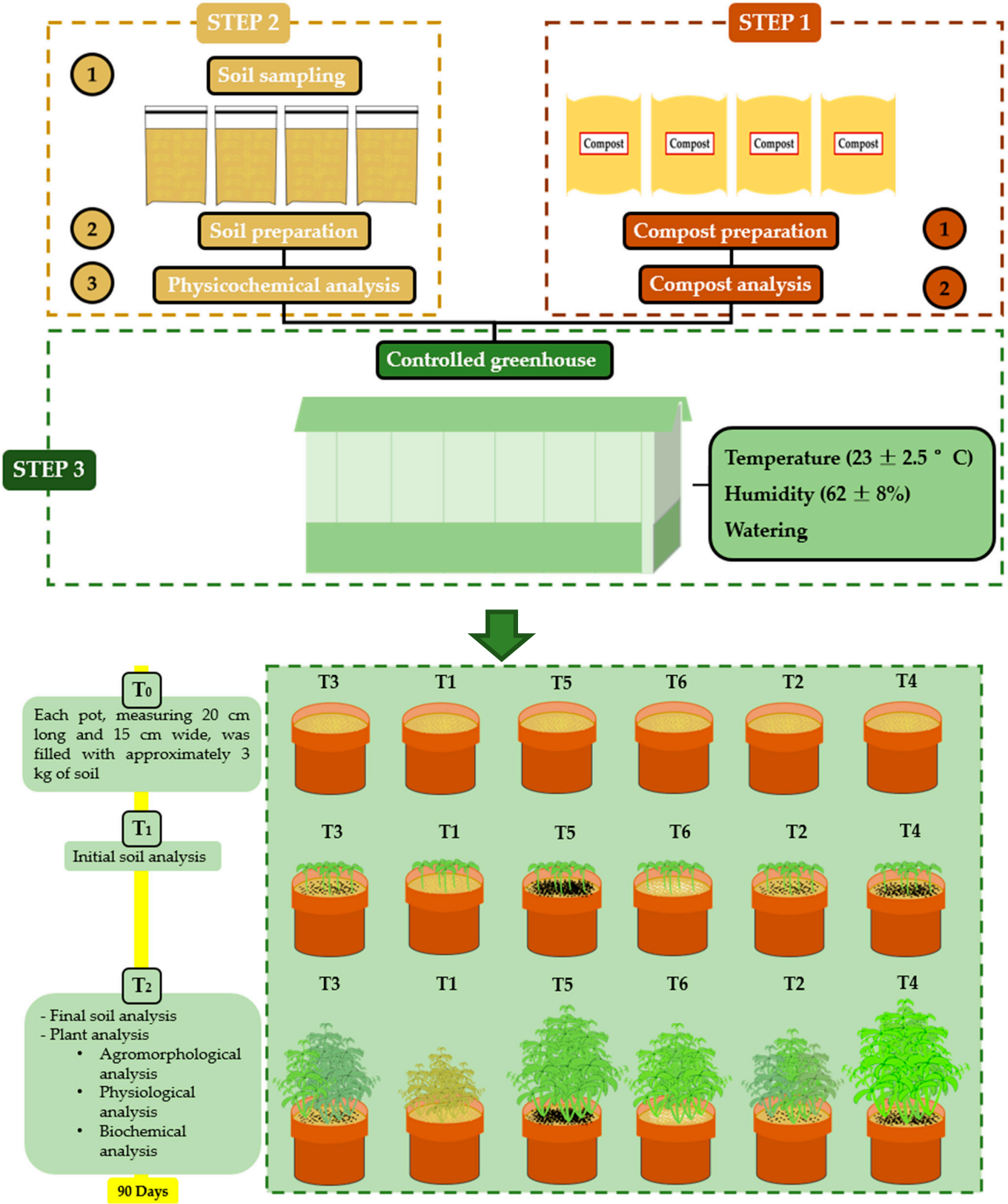


Figure 2. Flowchart of study design and methodology.

3. Results and Discussion

3.1. Impact of Compost Application on Soil's Physicochemical Attributes

Soil pH is a critical indicator of the overall condition of the plant growth medium, providing insights into nutrient availability, salinity levels, and the status of the soil microbial community [60]. It significantly influences plant growth performance [61,62]. The application of compost can influence soil pH levels by releasing organic acids during microbial decomposition, which contribute to a slight reduction in the soil's pH [63]. This decrease can enhance the solubility and bioavailability of essential nutrients, which are often less accessible in alkaline soils, thereby improving the plants' nutrient uptake [64]. The data presented in Table 2 demonstrate a significant decrease in pH values following the addition of compost across all treatments compared to the negative control.

Table 2. Soil chemical properties (pre-treatment and post-treatment analysis).

Soil Chemical Properties								
Samples	**PH**		**EC (µS/cm)**		**SOM (%)**		**SOC (%)**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
T1	7.35 ± 0.8^{b}	7.31 ± 0.52^{a}	201 ± 1.23^{f}	200 ± 0.23^{f}	1.29 ± 0.32^{f}	1.1 ± 0.24^{f}	0.75 ± 0.89^{f}	0.63 ± 0.65^{f}
T2	7.33 ± 0.15^{b}	7.31 ± 0.42^{a}	360 ± 0.36^{e}	358 ± 0.62^{e}	4.59 ± 0.65^{e}	4.2 ± 0.89^{e}	2.66 ± 0.97^{e}	2.43 ± 0.54^{e}
T3	7.29 ± 0.2^{c}	7.25 ± 1.02^{b}	486 ± 0.65^{d}	470 ± 0.15^{d}	7.06 ± 0.03^{d}	6.7 ± 0.65^{d}	4.09 ± 0.36^{d}	3.88 ± 0.12^{d}
T4	$7.26 + 0.35^{d}$	$7.22 \pm 0.94^{b,c}$	632 ± 1.23^{c}	658 ± 1.15^{c}	13.71 ± 0.21^{b}	12.8 ± 0.15^{b}	7.95 ± 0.87^{b}	7.42 ± 0.01^{b}
T5	7.22 ± 2.01^{e}	7.18 ± 1.21^{c}	858 ± 0.78^{a}	803 ± 0.25^{a}	14.62 ± 0.42^{a}	13.2 ± 0.23^{a}	8.48 ± 0.23^{a}	7.65 ± 0.12^{a}
T6	7.42 ± 0.35^{a}	7.32 ± 1.36^{a}	704 ± 0.66^{b}	700 ± 2.01^{b}	1.28 ± 0.32^{f}	1.12 ± 0.24^{f}	0.75 ± 0.92^{f}	0.63 ± 0.67^{f}
Soil chemical properties								
Samples	**Av. N (%)**		**Ex. K (mg/kg)**		**Av. P (mg/kg)**		**Ca (mg/kg)**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
T1	0.07 ± 0.23^{c}	0.05 ± 0.89^{c}	41.25 ± 0.25^{f}	32.5 ± 0.65^{f}	31.85 ± 0.54^{f}	24.77 ± 0.81^{f}	16.5 ± 0.66^{e}	13 ± 0.01^{f}
T2	0.13 ± 0.65^{b}	0.11 ± 0.58^{b}	330 ± 2.15^{e}	315 ± 1.33^{e}	50.85 ± 0.78^{e}	48.37 ± 1.54^{e}	$21.5 \pm 0.21^{d,e}$	19 ± 2.36^{e}
T3	0.13 ± 0.54^{b}	$0.11 \pm 0.26^{a,b}$	495 ± 0.17^{d}	460 ± 0.26^{d}	59.34 ± 0.64^{d}	57.69 ± 0.96^{d}	27.5 ± 0.20^{d}	23 ± 1.23^{d}
T4	$0.16 \pm 0.84^{a,b}$	$0.13 \pm 0.14^{a,b}$	555 ± 1.66^{c}	525 ± 0.63^{c}	81.17 ± 0.98^{c}	77.04 ± 1.23^{c}	37.5 ± 0.36^{c}	32 ± 0.75^{c}
T5	$0.13 \pm 0.78^{a,b}$	$0.11 \pm 2.6^{a,b}$	1612.5 ± 0.55^{b}	1475 ± 0.42^{b}	82.94 ± 0.33^{b}	80.70 ± 0.45^{b}	60 ± 0.66^{a}	52.5 ± 0.42^{a}
T6	0.17 ± 0.99^{a}	0.14 ± 0.14^{a}	1825 ± 0.69^{a}	1725 ± 0.25^{a}	105.48 ± 1.22^{a}	100.52 ± 0.33^{a}	50 ± 0.75^{b}	46 ± 0.55^{b}
Soil chemical properties								
Samples	**Mg (mg/kg)**		**CEC cmol/kg**					
	Initial	**Final**	**Initial**	**Final**				
T1	21.5 ± 0.66^{c}	17 ± 0.14^{f}	11 ± 0.43^{e}	9 ± 0.54^{d}				
T2	28.5 ± 0.23^{b}	25.5 ± 1.65^{e}	14 ± 0.58^{d}	11 ± 0.87^{d}				
T3	30.05 ± 0.41^{b}	27 ± 1.66^{d}	22 ± 0.32^{c}	20 ± 0.31^{c}				
T4	32.5 ± 0.84^{b}	29 ± 0.98^{c}	28 ± 0.25^{b}	23 ± 1.65^{b}				
T5	45 ± 0.55^{a}	35 ± 1.85^{b}	35 ± 1.26^{a}	28 ± 0.51^{a}				
T6	50 ± 0.32^{a}	44 ± 0.63^{a}	24 ± 0.54^{c}	$22 \pm 0.15^{b,c}$				

Note: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean values a < b < c < d < e < f, n = 4 replicates.

The initial pH values for treatments T1, T2, T3, T4, T5, and T6 were 7.35, 7.33, 7.29, 7.26, 7.22, and 7.42, respectively. By the end of the experiment, the pH levels decreased to reach 7.31, 7.31, 7.25, 7.22, 7.18, and 7.32, respectively. This slight decrease in soil pH is attributed to the slightly acidic nature of the compost (Table 1). The reduction in pH can be also linked to the release of hydrogen ions and the organic and inorganic compounds introduced into the soil through the application of compost, as well as chemical reactions between the compost and soil substrates [65].

EC is a crucial parameter in crop management, reflecting the soil's nutrient availability and salinity levels. The data presented in Table 2 indicated a significant increase in soil EC following the application of compost (T2, T3, T4, and T5) compared to the negative

control (T1). This significant initial rise in EC can be attributed to the enhanced nutrient content introduced by the compost. However, by the end of the experiment, a notable decrease in soil EC was observed, which can be explained by the nutrient uptake by basil plants for growth. Additionally, the application of compost led to changes in the soil's physical properties, such as TP and WHC (Table 3), further influencing the solubility and the dynamics of Na^+, Cl^-, and HCO_3 [66].

Table 3. Soil physical properties (pre-treatment and post-treatment analysis).

Soil physical properties								
Samples	**WHC (%)**		**IR (m/s)**		**BD (g/cm^3)**		**TP (%)**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
T1	32 ± 0.23 ^{e}	35 ± 0.58 ^{e}	3.32 ± 0.74 ^{f}	6.1 ± 0.64 ^{a}	1.5 ± 0.34 ^{a}	1.51 ± 0.54 ^{a}	40.39 ± 0.17 ^{e}	40.32 ± 0.54 ^{e}
T2	50 ± 0.78 ^{d}	53 ± 0.75 ^{d}	4.45 ± 0.61 ^{d}	5.1 ± 0.84 ^{b}	1.4 ± 0.47 ^{a,b}	1.4 ± 1.65 ^{b}	43.2 ± 0.61 ^{d}	43 ± 0.35 ^{d}
T3	69 ± 0.65 ^{c}	68 ± 0.62 ^{c}	5.56 ± 0.54 ^{c}	3.2 ± 0.71 ^{c}	1.2 ± 0.66 ^{c,d}	1.22 ± 0.23 ^{c}	49 ± 0.75 ^{c}	49.2 ± 0.05 ^{c}
T4	97 ± 1.65 ^{b}	98 ± 1.24 ^{b}	7.23 ± 0.65 ^{b}	2.6 ± 0.64 ^{d}	1.05 ± 1.47 ^{d}	1.09 ± 0.17 ^{d}	52 ± 0.56 ^{b}	52 ± 0.01 ^{b}
T5	110 ± 0.85 ^{a}	112 ± 0.48 ^{a}	7.78 ± 0.76 ^{a}	1.4 ± 0.47 ^{e}	0.9 ± 1.36 ^{e}	0.97 ± 0.26 ^{e}	58 ± 0.97 ^{a}	57.5 ± 0.19 ^{a}
T6	52 ± 0.74 ^{d}	51 ± 0.36 ^{d}	3.61 ± 0.87 ^{e}	5.1 ± 0.21 ^{b}	1.3 ± 0.58 ^{b,c}	1.1 ± 0.74 ^{d}	41 ± 0.71 ^{e}	41 ± 0.65 ^{e}

Soil physical properties								
Samples	**WRC (%)**		**Particle size distribution (%)**					
			>3 mm		**3–2 mm**		**2–1 mm**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
T1	17 ± 0.21 ^{e}	16 ± 0.22 ^{e}	43 ± 0.65 ^{a}	44 ± 0.48 ^{a}	36.8 ± 1.65 ^{d}	35.8 ± 0.62 ^{d}	15.1 ± 0.15 ^{c}	15.1 ± 0.41 ^{c,d}
T2	21 ± 0.64 ^{d}	20.8 ± 0.81 ^{d}	42 ± 0.61 ^{a,b}	42 ± 0.47 ^{a,b}	37.8 ± 0.15 ^{c,d}	37.5 ± 0.25 ^{c,d}	16.1 ± 0.51 ^{b,c}	16.4 ± 0.62 ^{a,b}
T3	25 ± 0.14 ^{c}	24.9 ± 0.61 ^{c}	39 ± 0.17 ^{c}	40 ± 0.15 ^{b}	39 ± 0.65 ^{b,c}	38 ± 0.15 ^{b,c}	16 ± 0.26 ^{b,c}	15 ± 0.11 ^{d}
T4	32 ± 0.75 ^{b}	32 ± 0.97 ^{b}	40 ± 0.64 ^{b,c}	41 ± 0.65 ^{b}	40 ± 0.26 ^{b}	40 ± 0.18 ^{a,b}	16.8 ± 0.25 ^{a,b}	15.8 ± 0.02 ^{b,c,d}
T5	35 ± 0.66 ^{a}	35 ± 0.17 ^{a}	34 ± 1.31 ^{d}	34 ± 0.17 ^{c}	43 ± 0.16 ^{a}	43 ± 0.11 ^{a}	17.3 ± 0.48 ^{a}	17.3 ± 0.28 ^{a}
T6	19 ± 0.64 ^{d,e}	19 ± 0.44 ^{d}	42 ± 0.23 ^{a,b}	42 ± 0.18 ^{a,b}	37 ± 0.29 ^{c,d}	37 ± 0.55 ^{c,d}	16.1 ± 1.51 ^{b,c}	16.1 ± 0.26 ^{b,c}

Soil physical properties				
Samples	**Particle size distribution (%)**			
	1–0.25 mm		**<0.25 mm**	
	Initial	**Final**	**Initial**	**Final**
T1	3.9± 0.25 ^{b,c}	3.9 ± 0.64 ^{b,c}	1.2 ± 0.12 ^{c}	1.2 ± 0.66 ^{c}
T2	3.1 ± 0.21 ^{c,d}	3.1 ± 0.41 ^{c,d}	1 ± 0.15 ^{c,b}	1 ± 0.15 ^{c,b}
T3	4.5 ± 0.15 ^{a,b}	4.5 ± 1.35 ^{a,b}	1.5 ± 0.26 ^{b}	1.5 ± 0.66 ^{b}
T4	2.4 ± 0.01 ^{d}	2.4 ± 0.98 ^{d}	0.8 ± 0.17 ^{d,e}	0.8 ± 0.55 ^{d,e}
T5	5 ± 0.15 ^{a}	5 ± 0.18 ^{a}	0.7 ± 0.61 ^{e}	0.7 ± 0.11 ^{e}
T6	3.1 ± 0.54 ^{c,d}	3.1 ± 0.71 ^{c,d}	1.8 ± 0.12 ^{a}	1.8 ± 0.64 ^{a}

Note: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean values a < b < c < d < e < f, n = 4 replicates.

SOM is a critical factor in maintaining soil fertility and productivity, influencing various properties and processes such as nutrient cycling, soil structure, aeration, and water retention [67]. Maintaining and enhancing SOM content requires the application of adequate organic and inorganic fertilizers [68]. In this study, the SOM content was gradually increased by raising the compost rate (Table 2). The treatment with the highest compost rate (T5) exhibited the highest SOM content compared to the other organic treatments (T2, T3, and T4) and the NPK dose (T6). Initially, the SOM value was 1.29%, increasing to reach 4.59%, 7.06%, 13.71%, 14.62%, and 12.32%, for T2, T3, T4, T5, and T6, respectively (Table 2). The results demonstrate that the highest organic compost application (T5) significantly enhances SOM more effectively than NPK treatment (T6), thereby safeguarding long-term soil fertility and productivity. However, by the end of the experiment, SOM content decreased across all treatments, attributed to basil's nutrient uptake for growth and the nutrient leaching due to water movement, particularly in treatments with lower compost

rates, where the soil structure remains fragile. These findings align with a previous study by Das et al. [22], indicating that high rates of organic enhancer application, without chemical fertilizers, significantly improve the soil quality, especially the SOM content.

SOC is an important component of SOM, significantly influencing the physical, chemical, and biological properties of the soil [69]. In this study, the initial SOC level was 0.75%, but the addition of compost significantly increased this value, with the highest SOC observed in treatment T5, where the absolute value increased by 7.73 times higher than in the treatment with chemical fertilizer (T6). This rise in SOC is attributed to the compost's rich OM content (Table 2), which enhances the SOC levels and stimulates microbial activity. The improvement in the soil structure enhances the soil's ability to retain organic carbon, which directly increases the stock of SOC in the soil [70]. In contrast, chemical fertilizers, while providing readily available nutrients, do not contribute to SOM, resulting in a comparatively limited potential for increasing SOC. Our findings are consistent with a previous study conducted by Al-Suhaibani et al. [71], which confirms that good agricultural practices, such as the application of organic fertilizers or their combination with chemical fertilizers, can maintain higher carbon concentrations in the soil.

The Av. N, P, and K in soil are crucial for ensuring optimal soil fertility and overall health. These nutrients, are pivotal for plant growth across physical, chemical, biological, and agro-morphological properties [29], and they exhibit significant variability when different treatments are applied, as illustrated in Table 2. Chemical fertilizer (T6) notably enhances nutrient availability, demonstrating higher values compared to the organic treatments (T2, T3, T4, and T5) and negative control (T1). Conversely, organic fertilizers, particularly at higher rates like T5, show marked improvements over the control treatment (T1), highlighting its potential ecological benefits as an alternative to chemical fertilizer. Notably, organic compost enhances soil nutrient availability and addresses various soil issues (Table 3) besides the nutrient supply, which makes it a better alternative. It stimulates microbial activity, thereby enhancing the organic nutrients, and significantly increases the soil's CEC (Table 2), which is crucial for nutrient retention and plant uptake [22]. By increasing its CEC, compost improves the soil's ability to retain essential nutrients, thereby reducing leaching and promoting better nutrient availability for plants [72]. Moreover, compost's humus content stabilizes the soil structure, mitigating the leaching of nutrients and thereby improving the status of the nutrients in the soil [42].

In soil science, hydraulic properties, including WHC, IR, and WRC, are crucial indicators of soil quality and water management. In this study, it was observed that WHC and WRC values were significantly higher in T5 compared to the negative control T1, indicating substantial improvements due to the increased compost application rates (Table 3). Specifically, WHC and WRC reached 110% and 35% in T5, respectively, compared to initial values of 32% and 17% in T1. These findings highlight the positive impact of organic compost on the soil's hydraulic properties across different treatments, surpassing both positive and negative controls (T1 and T6). Increasing SOM significantly increases the soil structure by promoting aggregation and enhancing the porosity of the soil, which in turn boosts the soil's WHC [73]. This dynamic interaction contributes to enhancing the overall hydraulic properties of the soil. Additionally, IR showed a significant increase, in values ranging from 8.44% to 133.63% higher than T1. This enhancement is positively correlated with the SOM content, which is known to enhance the formation and stabilization of soil aggregates and thereby improve various soil physical functions, especially hydraulic properties [51,74]. Treatments with enhanced SOM levels (T4 and T5) exhibited improvements in TP and overall hydraulic properties. Al-Suhaibani et al. [71] also supports these findings, demonstrating that organic compost applications enhance SOM content and positively affect the soil's physical and hydraulic properties. For instance, İşler and Kavdır [75] examined the

impact of compost derived from olive pomace and vineyard pruning waste on soils with different textures. Their findings demonstrated that the application of only 6% compost significantly increased the total porosity by 14.26% in clay soils and enhanced the field capacity by 27.7% in sandy loam soils after over 200 days of incubation. Similarly, Reynolds et al. [76] investigated the impact of yard waste compost on the physical properties of a sandy loam soil. Their findings revealed that the application of compost increased soil porosity and improved soil structure. A recent study investigated the effect of various OAs on soil pore structure and reported that the application of biochar significantly increased the total porosity, achieving an increase of 54.28% [77]. As observed, these findings were attributed to the role of OAs in enhancing the overall soil health.

The incorporation of organic compost into soil stimulates microbial activity, which plays a crucial role in SOM decomposition and nutrient cycling, while reducing the dependency on chemical fertilizer's application [78]. The increased microbial diversity associated with compost's application contributes to improving soil aggregation and resilience and further enhancing soil fertility [79]. Previous studies have demonstrated that soils amended with organic compost exhibit a higher microbial respiration rate and enzymatic activities compared to chemically fertilized soils [80], reinforcing the link between compost's application, SOM's accumulation, and efficient long-term nutrient cycling.

A high SOM content plays a pivotal role in enhancing soil aggregate stability and TP, consequently influencing the BD and pore size distribution [31,73,81]. Initially characterized by a high BD of 1.5 g/cm^3, the soil underwent a significant improvement across all treatments. The results indicated substantial BD reductions, with values reaching, 1.4, 1.2, 1.05, 0.9, and 1.3 g/cm^3, in T2, T3, T4, T5, and T6, respectively (Table 3). These reductions ranged from 13.4% to 40%, highlighting the efficacy of treatments in enhancing the soil structure. By increasing SOM, compost facilitates carbon storage within the soil layers, thereby reducing concentrations of atmospheric carbon dioxide [16,42]. This mechanism contributes to climate change mitigation by improving the soil's ability to retain carbon, aligning with the objectives of the United Nations Sustainable Development Goals (SDGs).

The PSD remained relatively consistent from the initial to final measurements across all treatments, with only minor variations in each size fraction. T1 and T6 generally showed similar distributions, featuring the highest proportions of larger particles (>3 mm) and finer fractions (<0.25 mm), respectively. By contrast, T2–T5 exhibited slightly lower percentages in the >3 mm category and increased proportions in the mid-size fractions (3–2 mm, 2–1 mm, 1–0.25 mm). Notably, T5 showed the greatest shift toward mid-size particles (3–2 mm, 2–1 mm, 1–0.25 mm), which is consistent with compost's role in promoting aggregation and enhancing the soil structure. However, the overall alterations remained modest over the duration of the experiment. This indicates that while compost can subtly influence PSD in the short term, as evidenced by the trends observed in T5, major textural transformations may require a longer timeframe.

3.2. Impact of Compost Application on Plant's Morphologic, Physiologic, Agronomic, and Biochemical Attributes

Numerous studies have demonstrated that the integration of chemical and organic fertilizers significantly enhances crop yields, often achieving results comparable to the full recommended dose of chemical fertilizers alone [60,72]. The results of the present experiment revealed that the addition of 30 t/ha of compost (T4) and chemical fertilizers (T6) led to a considerable increase in the agronomical properties of the basil plants. Incorporating a high rate of compost (T4) alongside chemical fertilizer (positive control T6) resulted in significant improvements across various agronomic parameters, including SFW, SDW, SL, NL, NB, NF, PRL, RFW, RDW, ALL, ALW, and ALA. Notably, there was a marked reduction

in the NYL per plant, decreasing from 81.8% in T1 to 68.75% in T2, 19.60% in T3, 8.33% in T4, 13.79% in T5, and 2.94% in T6 (Table 4).

Table 4. Final agronomic characteristics of basil shoots and seeds.

Shoot						
Samples	**SFW (g)**	**SDW (g)**	**SL (cm)**	**NL**	**NB**	**NYL**
T1	67.3 ± 0.31 ^{f}	6.28 ± 0.91 ^{f}	15.3 ± 0.15 ^{f}	11 ± 0.15 ^{e}	4 ± 0.26 ^{d}	9 ± 0.15 ^{a}
T2	93.5 ± 0.26 ^{e}	10.29 ± 0.04 ^{e}	22.4 ± 0.16 ^{e}	32 ± 0.35 ^{d}	6 ± 0.84 ^{c,d}	22 ± 0.11 ^{a}
T3	152.6 ± 0.01 ^{d}	16.02 ± 0.61 ^{d}	35 ± 0.16 ^{d}	51 ± 0.74 ^{c}	8 ± 0.05 ^{c}	10 ± 0.66 ^{b}
T4	213.4 ± 0.11 ^{a}	25.6 ± 0.17 ^{a}	42 ± 0.21 ^{b}	60 ± 0.16 ^{b}	12 ± 0.22 ^{b}	5 ± 0.36 ^{c}
T5	201.15 ± 0.45 ^{b}	22.15 ± 0.56 ^{b}	39 ± 0.16 ^{c}	58 ± 0.35 ^{b}	11 ± 0.26 ^{b}	8 ± 0.05 ^{b}
T6	172.3 ± 0.25 ^{c}	17.23 ± 0.84 ^{c}	45 ± 0.61 ^{a}	68 ± 0.62 ^{a}	17 ± 0.51 ^{a}	1.5 ± 0.61 ^{d}
	Shoot				**Seeds**	
Samples	**NF**	**Av. N (%)**	**P (%)**	**K (%)**	**Weightof 100 Seeds (g)**	
T1	10 ± 0.36 ^{f}	1.1 ± 0.36 ^{e}	0.15 ± 0.26 ^{f}	1.20 ± 0.05 ^{f}	0.19 ± 0.11 ^{e}	
T2	22 ± 0.54 ^{e}	1.92 ± 0.65 ^{d}	0.17 ± 0.26 ^{e}	1.22 ± 0.32 ^{e}	0.22 ± 0.62 ^{d}	
T3	37 ± 0.30 ^{d}	2.14 ± 0.31 ^{c}	0.24 ± 0.42 ^{d}	1.24 ± 0.14 ^{d}	0.28 ± 1.63 ^{c}	
T4	63 ± 0.22 ^{b}	2.42 ± 0.14 ^{b}	0.26 ± 0.62 ^{b}	1.72 ± 1.66 ^{b}	0.32 ± 0.69 ^{b}	
T5	59 ± 1.32 ^{c}	2.23 ± 0.62 ^{c}	0.25 ± 0.75 ^{c}	1.68 ± 1.80 ^{c}	0.34 ± 0.35 ^{a,b}	
T6	72 ± 1.65 ^{a}	2.8 ± 0.17 ^{a}	0.28 ± 0.95 ^{a}	2.2 ± 0.36 ^{a}	0.35 ± 0.36 ^{a}	
	Root					
Samples	**PRL (cm)**	**RFW (g)**	**RDW (g)**			
T1	15.3 ± 0.22 ^{f}	6.4 ± 0.47 ^{f}	1.34 ± 0.54 ^{f}			
T2	18.2 ± 0.36 ^{e}	9.2 ± 0.31 ^{e}	2.04 ± 0.65 ^{e}			
T3	18.95 ± 0.75 ^{d}	10.3 ± 0.18 ^{d}	2.28 ± 0.65 ^{d}			
T4	22.4 ± 0.63 ^{b}	13.5 ± 0.88 ^{b}	2.56 ± 0.64 ^{b}			
T5	21.5 ± 0.15 ^{c}	12.8 ± 0.69 ^{c}	2.8 ± 0.64 ^{c}			
T6	23.6 ± 0.61 ^{a}	13.9 ± 0.79 ^{a}	3.19 ± 0.65 ^{a}			

Note: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean values a < b < c < d < e < f, n = 4 replicates.

Agronomic values between T6 and T4 were comparable, although chemical fertilizer showed superiority in seed nutrient content and weight. Specifically, the Av. N, P, and K content were significantly higher in T6 compared to T4 (15.7%, 9.89%, and 27.68% respectively), and there was a 9.4% increase in the weight of a 100 seeds (Table 4).

These findings indicate minimal differences between the effects of 30 t/ha of compost and chemical fertilizer. Chemical fertilizers promote rapid plant growth through immediate nutrient availability, whereas compost offers a balanced nutrient supply with a slow release over time, gradually enriching the soil with SOM. This slow process improves the soil's properties and nutrient-holding capacity and positively influences the physiological and biochemical properties of the plants [4]. Moreover, the 30 t/ha compost application rate likely optimized the balance of essential nutrients, thereby facilitating nutrient availability to the plants. This optimal nutrient distribution supported the plants' physiological processes, which in turn promoted the plants' growth and development. In the physiological attributes of basil plants, the application of compost demonstrated beneficial effects on plant growth (Table 5). The MSI values increased from 50.1% in T1 to reach 90.5% in T4 and 91.4% in T6, indicating significant improvement.

Table 5. Final physiological and morphological characteristics of basil leaves.

Leaf					
Samples	**MSI (%)**	**RWC (%)**	**ALL (cm)**	**ALW (cm)**	**ALA (cm^2)**
T1	50.1 ± 0.62^{f}	51.4 ± 0.31^{e}	2.2 ± 0.34^{f}	17 ± 0.36^{e}	2.93 ± 0.61^{f}
T2	72.4 ± 0.16^{e}	73.2 ± 0.21^{c}	3.4 ± 0.36^{e}	2.15 ± 0.35^{d}	5.74 ± 0.36^{e}
T3	79.12 ± 0.36^{d}	79.4 ± 0.36^{b}	6.8 ± 0.36^{d}	3.5 ± 0.75^{c}	18.69 ± 0.25^{d}
T4	90.5 ± 0.15^{b}	84.4 ± 0.36^{a}	9.2 ± 0.36^{b}	3.8 ± 0.15^{b}	27.45 ± 0.36^{b}
T5	89.5 ± 0.14^{c}	84.3 ± 0.26^{a}	8.2 ± 0.35^{c}	$3.6 \pm 1.64^{a,b}$	23.18 ± 0.61^{c}
T6	91.4 ± 0.6^{a}	60.3 ± 0.20^{d}	9.5 ± 0.36^{a}	3.8 ± 0.31^{a}	28.35 ± 0.61^{a}
Leaf					
Samples	**Total Chlorophyll (mg/g FW)**	**Chlorophyll a (mg/g FW)**	**Chlorophyll b (mg/g FW)**	**EOC (%)**	
T1	2.11 ± 0.62^{e}	1.73 ± 0.36^{c}	0.38 ± 0.21^{c}	0.5 ± 0.22^{d}	
T2	2.57 ± 0.14^{d}	2.17 ± 1.62^{b}	$0.4 \pm 0.36^{b,c}$	$0.54 \pm 0.66^{c,d}$	
T3	2.7 ± 0.98^{c}	2.24 ± 0.31^{b}	$0.46 \pm 0.65^{b,c}$	0.62 ± 0.15^{c}	
T4	3.01 ± 0.15^{b}	2.48 ± 0.36^{a}	$0.53 \pm 0.36^{a,b}$	$0.83 \pm 0.78^{a,b}$	
T5	$2.92 \pm 0.62^{a,b}$	2.4 ± 0.60^{a}	$0.52 \pm 0.67^{a,b}$	0.74 ± 0.32^{b}	
T6	3.12 ± 0.71^{a}	2.5 ± 0.45^{a}	0.62 ± 0.75^{a}	0.93 ± 0.25^{a}	

Note: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean values a < b < c < d < e < f, n = 4 replicates.

Additionally, RWC showed significant enhancements, rising from 51.4% in T1 to 84.4% in T4 and 84.3% in T5. These improvements are attributed to the integration of organic treatment, which enhances SOM content and essential nutrient availability. This integration contributes to improving soil water retention, ultimately enhancing soil health and productivity.

The application of a high rate of compost significantly enhanced the chlorophyll content in the basil leaves (Table 5). Total chlorophyll, chlorophyll a, and chlorophyll b reached higher values in T4, measuring 3.01 mg/g FW, 2.48 mg/g FW, and 0.53 mg/g FW, respectively, and in T6, they reached 3.12 mg/g FW, 2.5 mg/g FW, and 0.62 mg/g FW, respectively. Furthermore, the EOC showed an increase ranging between 8% and 48% in the presence of compost.

Compost is recognized for its beneficial effects in enhancing soil's physicochemical and biological properties, consequently boosting plant growth and productivity. Previous studies have demonstrated that the incorporation of compost improves soil fertility, enhances agricultural production, and contributes to sustainable farming practices [75]. In this study, although treatment T5 resulted in a greater increase in SOM compared to T4, it did not lead to correspondingly higher plant growth metrics. This finding underscores the nuanced relationship between SOM's accumulation and plant performance. While elevated SOM typically improves soil structure, moisture retention, and nutrient-holding capacity [16], these advantages do not always produce immediate gains in plant development. One possible explanation is that higher SOM levels may alter soil microbial activity and nutrient-cycling processes, thereby affecting the nutrient availability to plants [18]. These results suggest that although SOM plays a critical role in enhancing long-term soil fertility, its short-term impact on plant growth can be influenced by a range of environmental and soil-specific factors.

3.3. Impact of Compost Application on Plant's and Soil's Heavy Metals Levels

The application of compost significantly influenced the accumulation of HM in the amended sandy loam soil. As shown in Table 6, metal concentrations increased in relation to the compost application rate, indicating a cumulative input of these elements via OAs.

Table 6. Post-harvest results of soil's and plant's heavy metals levels.

	Zn (mg/kg DM)		**Fe (mg/kg DM)**		**Mn (mg/kg DM)**	
Samples	**Soil**	**Plant**	**Soil**	**Plant**	**Soil**	**Plant**
T1	9	18	48	40	28	19
T2	20	25	52	55	60	22
T3	29	33	73	70	88	30
T4	42	42	85	81	90	35
T5	53	50	98	110	98	41
T6	9	20	50	45	30	2
	Cd (mg/kg DM)		**Pb (mg/kg DM)**		**Cu (mg/kg DM)**	
Samples	**Soil**	**Plant**	**Soil**	**Plant**	**Soil**	**Plant**
T1	0.22	0.014	5.3	0.09	3.2	1.2
T2	0.23	0.015	5.6	0.10	3.3	1.19
T3	0.25	0.016	5.42	0.08	3.4	1.3
T4	0.21	0.013	5.2	0.06	3.21	1.07
T5	0.25	0.015	5.3	0.11	3.4	1.19
T6	0.23	0.014	5.51	0.1	3.2	1.2

Notably, treatments T4 (30 t/ha) and T5 (40 t/ha) yielded the highest concentrations of Zn (42 and 53 mg/kg DM, respectively), Fe (85 and 98 mg/kg DM), and Mn (90 and 98 mg/kg DM) compared to the control soil (T1), which maintained baseline levels of Zn (9 mg/kg), Fe (48 mg/kg), and Mn (28 mg/kg). In addition to these micronutrients, the native sandy loam soil also contained trace levels of Cu (3.2–3.4 mg/kg), Pb (5.2–5.6 mg/kg), and Cd (0.21–0.25 mg/kg) across treatments, even though these metals were not detected in the compost itself. Their presence is attributable to natural geochemical background levels and possible residual legacy contamination.

This trend is consistent with prior studies indicating that compost derived from plant residues and manure can serve as a moderate source of micronutrients, including HM, that naturally occur in organic waste feedstocks [82]. The compost used in this study contained measurable concentrations of Zn (83 mg/kg), Fe (321 mg/kg), and Mn (230 mg/kg), which contributed to the gradual enrichment of the soil's total metal content without exceeding critical safety thresholds (Table 1).

The Zn levels remained well below the upper permissible limits for agricultural soils defined by international guidelines such as the European Commission (EC No. 2019/1009), which sets threshold values for Zn in 300 mg/kg [83]. Similarly, Fe, Mn concentrations observed across all treatments remained within the limit value set by the World Health Organization (WHO) [56,84,85]. Cu, Pb, and Cd concentrations in soil also stayed well below toxicity thresholds (100 mg/kg, 100 mg/kg, and 3 mg/kg respectively), further supporting the environmental safety of compost's application [86].

In addition, the soil's physicochemical improvements, such as an increased CEC, SOM, and WRC, may have reduced the mobility and bioavailability of these metals, thus mitigating any potential environmental risks (Tables 2 and 3). The enhanced organic matrix likely

promoted the complexation and stabilization of metal ions, reducing their leaching potential and ensuring a gradual release to plants [87]. The gradual increases in HM concentrations can be viewed as a beneficial outcome in the context of micronutrient replenishment for deficient soils, particularly in semi-arid zones where Zn and Mn deficiencies are common constraints to crop productivity [88].

The accumulation of trace HM in plant tissues is a critical indicator of the bioavailability of these elements in soil and the potential risk of transfer into the food chain [89]. As presented in Table 6, Zn concentrations ranged from approximately 18 mg/kg DW in the control treatment (T1) to 50 mg/kg DM under the highest compost application (T5). Similarly, Fe levels increased from 40 to 110 mg/kg DM, and Mn ranged from 19 to 41 mg/kg DM, reflecting the influence of compost on the metal uptake by plants. The concentrations of Cd (0.013–0.016 mg/kg), Pb (0.06–0.11 mg/kg), and Cu (1.07–1.3 mg/kg) detected in sweet basil tissues were low and remained consistently within acceptable levels for plants. These values are significantly below the internationally established safety limits for edible leafy vegetables. According to guidelines from the WHO and the Food and Agriculture Organization (FAO), the maximum permissible concentrations are 0.05 mg/kg for Cd, 0.3 mg/kg for Pb, and 10 mg/kg for Cu. Thus, basil cultivated under all compost treatments in this study meets safety standards for human consumption [58]. Importantly, no phytotoxicity symptoms were observed in any of the basil plants grown in compost-amended soils, which further suggests that the concentrations of trace metals remained within agronomically acceptable and environmentally safe levels in all the treatments.

The observed increase in trace metal content is attributable to the mineral composition of the compost, which served as a modest but effective source of micronutrients. Several studies have demonstrated that compost not only supplies essential micronutrients but also improves their bioavailability through chelation and enhanced root–microbe interactions, especially in sandy soils where nutrient retention is typically low [90]. Moreover, the increase in root biomass and improved soil physicochemical properties—such as CEC, porosity, and moisture content—likely facilitated better nutrient acquisition by the basil plants. These findings align with previous research indicating that compost amendments improve micronutrient uptake efficiency, especially under conditions of low inherent soil fertility [91].

The modest and controlled enrichment of basil tissues with Zn, Fe, and Mn observed in this study can be considered agronomically beneficial. Zn is essential for auxin metabolism and membrane integrity, Fe is critical for chlorophyll synthesis and respiration, while Mn functions as a cofactor in numerous enzymatic processes, including photosynthesis and antioxidant ones [88]. Thus, their increased presence may partially explain the enhanced physiological performance observed in treatments T4 and T5, such as an elevated chlorophyll content, MSI, and EOC.

To further evaluate the capacity of basil to accumulate metals from the soil, the ACF was calculated for each metal and treatment (Table 7).

Table 7. Accumulation factor of metal content (ACF) from soil to plant.

Samples	ACF-Zn	ACF-Fe	ACF-Mn	ACF-Cd	ACF-Pd	ACF-Cu
T1	2.00	0.83	0.68	0.064	0.017	0.375
T2	1.25	1.06	0.37	0.065	0.018	0.361
T3	1.14	0.96	0.34	0.064	0.015	0.382
T4	1.00	0.95	0.39	0.062	0.012	0.333
T5	0.94	1.12	0.42	0.060	0.021	0.350
T6	2.22	0.90	0.07	0.061	0.018	0.375

ACF, defined as the ratio between metal content in plant tissue and the total concentration in soil, provides insights into metal mobility and plant uptake efficiency [92]. Across all treatments, ACF values for Cd, Pb, and Cu remained well below 0.07, 0.02, and 0.4, respectively, indicating the minimal translocation of toxic elements into edible tissues. In contrast, Zn and Fe exhibited moderate-to-high ACFs, particularly in T1 (Zn) and T5 (Fe), reflecting an efficient uptake of essential micronutrients. Notably, treatment T4 exhibited a ACF-Zn of 1.00 and ACF-Fe of 0.95, confirming a highly balanced and safe nutrient acquisition profile. The Mn ACF in T4 was 0.39, which also reflects a steady but controlled uptake [93]. These values reinforce the role of T4 as the ideal dose, achieving the optimal bioavailability of nutrients without enhancing food chain contamination risks. Interestingly, the T4 treatment achieved an optimal balance, providing high levels of beneficial micronutrients while avoiding an excessive accumulation, thereby representing the most agronomically efficient and environmentally safe compost dose.

Nevertheless, continuous long-term applications warrant careful monitoring, as an excessive accumulation over multiple cropping seasons may pose environmental and health concerns. Establishing a routine for soil and plant metal surveillance is thus recommended, particularly when using composts rich in micronutrients or sourced from variable organic waste streams.

3.4. Statistical Analysis Results

The correlation analysis of soil and plant parameters demonstrates the significant positive impacts of compost's application on basil plants in sandy soil (Table 8).

SOM exhibited strong positive correlations with essential soil nutrients and plant growth parameters, such as SOC (r = 1), K (r = 0.866), P (r = 0.713), Ca (r = 0.943), Mg (r = 0.855), CEC (r = 1), WHC (r = 0.756), IR (r = 0.844), WRC (r = 0.796), SFW (r = 0.955), SDW (r = 0.900), SL (r = 0.855), the weight of a 100 seeds (r = 0.855), MSI (r = 0.700), RWC (r = 0.752), TCh (r = 0.820), EOC (r = 0.923), PRL (r = 0.742), RFW (r = 0.767), and RDW (r = 0.804). These correlations suggest that higher SOM levels are integral to enhancing nutrient availability and overall plant health.

High SOM levels were also negatively correlated with BD (r = −1), indicating an improved soil structure, which facilitates root growth and nutrient uptake. The enhanced WHC showed strong positive correlations with various parameters such as IR (r = 0.986), TP (r = 1), WRC (r = 1), SFW (r = 0.771), SDW (r = 0.842), SL (r = 0.855), RWC (r = 0.943), and PRL (r = 0.756). These findings underscore the role of WHC in maintaining soil moisture, which is crucial for plant growth, especially in sandy soils prone to rapid water drainage. Positive correlations with SL (r = 0.371), the weight of a 100 seeds (r = 0.429), MSI (r = 0.371), TCh (r = 0.444), EOC (r = 0.422), RFW (r = 0.555), and RDW (r = 0.429) further emphasize the multifaceted benefits of an improved WHC on plant vigor and productivity.

TP displayed strong positive correlations with WRC (r = 1), SFW (r = 0.871), SDW (r = 0.903), and RWC (r = 0.943) and positive correlations with SL (r = 0.371), the weight of a 100 seeds (r = 0.429), MSI (r = 0.371), TCh (r = 0.421), EOC (r = 0.451), PRL (r = 0.372), RFW (r = 0.301), and RDW (r = 0.329). This indicates better cell integrity and stress resistance, suggesting that improved soil porosity contributes to enhanced plant resilience and yields.

WRC showed significant strong positive correlations with SFW (r = 0.771), SDW (r = 0.841), and RWC (r = 0.943) and positive correlations with the weight of a 100 seeds (r = 0.429), MSI (r = 0.371), TCh (r = 0.352), EOC (r = 0.342), PRL (r = 0.364), RFW (r = 0.401), and RDW (r = 0.429). These correlations highlight the importance of WRC in sustaining plant growth by ensuring consistent moisture availability.

Table 8. Correlation coefficients among soil and plant parameters.

Variables	pH	EC	SOM	SOC	Av. N	K	P	Ca	Mg	CEC	WHC	IR	BD	TP	WRC	SFW	SDW	SL	Weight of 100 Seeds	MSI	RWC	TCh	EOC	PRL	RFW	RDW
pH	1																									
EC	−0.406	1																								
SOM	−0.638	0.903	1																							
SOC	−0.548	0.743	1.000	1																						
Av. N	−0.144	0.425	0.377	0.555	1																					
K	−0.216	0.842	0.866	0.800	0.752	1																				
P	−0.116	0.782	0.713	0.855	0.841	1.000	1																			
Ca	−0.406	1.000	0.943	0.785	0.638	0.785	0.943	1																		
Mg	−0.306	0.789	0.855	0.815	0.820	1.000	1.000	0.943	1																	
CEC	−0.638	0.874	1.000	1.000	0.577	0.785	0.829	0.951	0.855	1																
WHC	−0.899	0.657	0.756	0.885	0.254	0.475	0.429	0.657	0.429	0.766	1															
IR	−0.868	0.754	0.844	0.885	0.308	0.541	0.551	0.754	0.551	0.855	0.986	1														
BD	0.518	−0.943	−1.000	−1.000	−0.577	−0.855	−0.829	−0.943	−0.751	−1.000	−0.829	−0.899	1													
TP	−0.899	0.601	0.525	0.851	0.155	0.429	0.320	0.657	0.429	0.886	1.000	0.986	−0.786	1												
WRC	−0.751	0.655	0.796	0.801	0.255	0.349	0.429	0.657	0.420	0.856	1.000	0.756	−0.929	1.000	1											
SFW	−0.552	0.888	0.955	0.962	0.698	0.884	0.771	0.829	0.781	0.753	0.771	0.802	−0.753	0.871	0.771	1										
SDW	−0.545	0.859	0.900	0.955	0.698	0.455	0.771	0.777	0.801	0.843	0.842	0.741	−0.863	0.903	0.841	1.000	1									
SL	−0.058	0.855	0.751	0.771	0.941	0.855	0.943	0.755	0.943	0.746	0.371	0.493	−0.521	0.371	0.321	0.829	0.829	1								
Weight of 100 seeds	−0.116	0.943	0.855	0.829	0.820	1.000	1.000	0.943	1.000	0.829	0.429	0.551	−0.829	0.429	0.429	0.841	0.771	0.943	1							
MSI	−0.058	0.829	0.700	0.901	0.941	0.785	0.943	0.829	0.893	0.746	0.371	0.493	−0.801	0.371	0.371	0.655	0.712	1.000	0.753	1						
RWC	−0.841	0.543	0.752	0.585	0.334	0.236	0.371	0.543	0.511	0.782	0.943	0.928	−0.762	0.943	0.943	0.763	0.827	0.429	0.371	0.429	1					
TCh	−0.055	0.845	0.820	0.752	0.901	0.943	0.894	0.885	0.744	0.755	0.444	0.455	−0.541	0.421	0.352	0.871	0.719	1.000	0.743	1.000	0.444	1				
EOC	−0.014	0.875	0.923	0.700	0.985	0.852	0.751	0.806	0.813	0.880	0.422	0.469	−0.521	0.451	0.342	0.903	0.909	1.000	0.843	1.000	0.477	1.000	1			
PRL	−0.010	0.753	0.742	0.712	0.748	0.759	0.722	0.751	0.783	0.726	0.756	0.526	−0.771	0.372	0.364	0.852	0.789	1.000	0.943	1.000	0.464	1.000	1.000	1		
RFW	−0.005	0.806	0.767	0.755	0.888	0.855	0.788	0.759	0.901	0.785	0.555	−0.393	−0.741	0.301	0.471	0.791	0.629	1.000	0.789	1.000	0.419	1.000	1.000	1.000	1	
RDW	−0.114	0.943	0.804	0.829	0.820	1.000	1.000	0.943	1.000	0.829	0.429	−0.551	−0.829	0.329	0.429	0.786	0.771	0.823	1.000	0.823	0.371	0.754	0.823	0.713	0.731	1

MSI was strongly positively correlated with TCh (r = 1), EOC (r = 1), PRL (r = 1), RFW (r = 1), and RDW (r = 0.823) and positively correlated with RWC (r = 0.429). These relationships indicate that MSI, a measure of plant cell integrity under stress, is closely linked to essential physiological and growth parameters. RWC showed significant positive correlations with TCh (r = 0.444), EOC (r = 0.477), PRL (r = 0.464), RFW (r = 0.419), and RDW (r = 0.371), while TCh demonstrated strong positive correlations with EOC (r = 1), PRL (r = 1), RFW (r = 1), and RDW (r = 0.754). This suggests that higher RWC and TCh levels are crucial for maintaining plant health and productivity under varying environmental conditions.

The PCA assessed various variables and showed the correlations based on factor loadings from each principal component (PC). The PCs explain the proportion of variance, allowing the identification of the influential parameters driving differences in soil health and plant growth across the treatments used. Two PCs were extracted, explaining 95.81% of the data variance. The two components (PC1–PC2) accounted for over 95.81% of the total data, indicating that the factors influencing physicochemical, agronomical, and morphological properties are contained within these components (Figure 3).

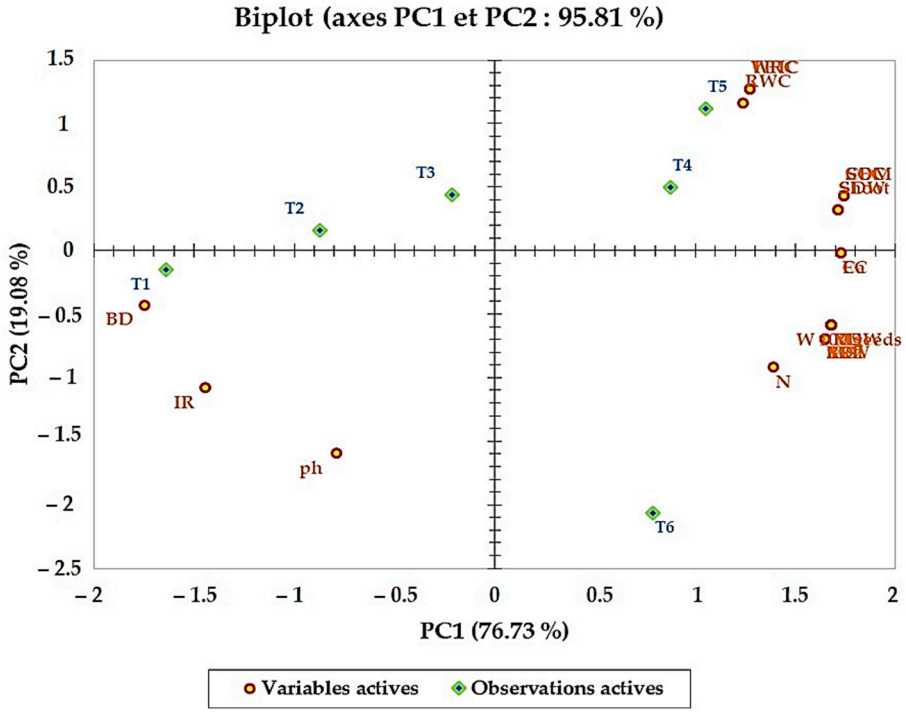


Figure 3. Principal component analysis for soil and basil plant properties.

PC1 explained 76.73% of the total variation, with a strong positive insert (>0.750) for many variables such as EC, SOM, SOC, Av. N, K, P, Ca, Mg, CEC, WHC, TP, WRC, SFW, SDW, SL, the weight of a 100 seeds, and PRL. In reverse, PC1 showed a negative correlation with pH, BD, TC, and EOC. These findings showed that PC1 is primarily associated with the soil's structure and fertility, as well as the overall productivity of the basil plants. The strong positive loadings of primary nutrients and growth parameters on PC1 suggest that higher levels of these variables significantly contribute to improved soil and plant health. Conversely, the negative correlation of PC1 with pH, BD, TC, and EO indicates that these factors are inversely related to the beneficial effects observed with compost's application on soil and plant health.

4. Discussion of the Findings, Study Limitations, and Future Recommendations

4.1. Plant Growth, Soil Health, Environmental Impact, and Economic Viability: An Integrated Perspective

This study provides a compelling argument for the substitution of synthetic fertilizers with organic compost, highlighting its multifaceted benefits from environmental, physiological, morphological, and agronomic perspectives. On the pollution mitigation front, the application of compost significantly enhanced SOC and SOM content, both of which are critical in CS and mitigating atmospheric CO_2 levels. The incorporation of compost not only improved the soil's CEC, WHC, and porosity but also supported the long-term immobilization of HM and minimized the risk of nutrient leaching, thereby contributing to reduced environmental contamination [94]. Furthermore, the absence of harmful chemical residues aligns with sustainable agricultural practices and helps in producing cleaner, organic-certified crops.

By enhancing nutrient availability, soil fertility, and plant productivity using OAs, the improvements align directly with SDGs, particularly SDG 2 (zero hunger) by improving resilient sustainable agricultural practices, SDG 13 (climate action) by encouraging carbon sequestration and reducing the emission of GHGs, and SDG 12 (responsible consumption and production) by supporting the recycling and reuse of organic waste [95]. By integrating soil management strategies that mitigate environmental degradation, enhance food security, and promote climate resilience, our finding reinforces the critical role of OAs in achieving long-term sustainability.

From an agronomic standpoint, the results clearly demonstrated that compost-treated soils fostered improved plant growth metrics—ranging from shoot and root biomass to EOC and chlorophyll concentration. Treatment T4 (30 t/ha) yielded results comparable to those from chemical fertilization (T6), confirming the hypothesis that compost can match or surpass chemical inputs in promoting plant vigor. The observed enhancement in parameters such as ALA, NF, MSI, and RWC further underscores the physiological robustness imparted by compost. This is particularly relevant for semi-arid regions with sandy soils, where maintaining soil fertility and moisture retention is often challenging [30].

Economically, compost offers a viable and cost-effective alternative to chemical fertilizers [96]. While chemical fertilizers provide rapid nutrient availability, they are associated with escalating prices, soil degradation, and dependency. Compost, derived from locally available waste, promotes a circular economy by transforming organic waste into a valuable agricultural input [97]. The enhancement in yield parameters, particularly seed weight and EOC, suggests that the economic return per hectare could potentially increase with compost's application. Moreover, the potential to reduce synthetic input use by up to 100%, as shown in this study, indicates long-term savings for farmers and contributes to sustainable food systems, particularly in low-income and middle-income agricultural settings.

4.2. Study Limitations and Future Recommendations

While the results of this study strongly support the use of organic compost as a sustainable amendment for improving soil fertility and basil's productivity, several limitations must be acknowledged. Firstly, the experiment was conducted under controlled greenhouse conditions, which do not fully replicate the environmental complexities of open-field cultivation. Greenhouses offer uniform microclimatic conditions, a stable temperature and humidity, and protection from wind or rainfall that are rarely encountered in field conditions. This consistency can significantly influence the plants' response and may mask the variability typically observed in natural environments. Moreover, the limited root zone in pots restricts root expansion and may alter the nutrient uptake and water dynamics,

potentially skewing the plants' development compared to their unrestricted field-grown counterparts. In open-field settings, additional factors such as solar radiation fluctuations, wind exposure, soil heterogeneity, and pest pressure can all significantly impact the performance of compost amendments. Therefore, large-scale field trials across multiple agroecological zones are essential to validate the transferability of greenhouse results to practical, real-world farming systems.

Furthermore, while compost offers various agronomic and environmental benefits, it is important to recognize potential barriers to its widespread agricultural adoption. One such limitation involves the economic and logistical challenges associated with compost production. The cost of raw materials, the labor-intensive nature of composting, and the expenses related to transportation and field application may exceed those of conventional chemical fertilizers, particularly in regions lacking an established composting infrastructure. Additionally, the accessibility of suitable organic waste is not uniform; rural or remote areas may face difficulties in sourcing adequate feedstocks for composting. These factors can limit the scalability and attractiveness of compost use, especially for smallholder farmers operating under constrained financial conditions. Nevertheless, these challenges can be mitigated through policy support, awareness campaigns, and investments in decentralized composting facilities that promote localized production and use. Facilitating farmer training on composting techniques and integrating compost use into national sustainable agriculture strategies can further accelerate its adoption.

A future research priority should also include a comprehensive investigation into the impact of compost on the soil microbiome. While this study documented significant improvements in the soil's physical and chemical parameters, the biological dimension—particularly microbial diversity, enzymatic activity, and soil respiration—remains unexplored. Compost's application is known to enhance the microbial biomass and functional diversity, which are pivotal for long-term soil fertility, organic matter decomposition, and plant–microbe interactions. Employing molecular tools such as metagenomics or quantitative PCR in future trials would provide deeper insights into the compost-induced shifts in microbial community composition and function. Understanding these microbial pathways would allow researchers and practitioners to optimize compost formulations for the maximum agronomic and ecological benefit.

5. Conclusions

This short-term study carried out on the application of organic compost in the fertilization of basil plants on sandy loam soil represents an original investigation into the interactions among these three components. The experiment yielded valuable data for the agronomic evaluation of various compost rates on soil with deficiencies in nutrients, organic matter, and structure, as well as on crop productivity. The findings demonstrated that the use of OAs such as compost at a high application rate (30 t/ha) had considerable beneficial effects on soil fertility and crop yields.

The primary aim of this work was to evaluate the effect of an organic fertilizer on the growth of *Ocimum basilicum* in sandy loam soil. The results indicated that the compost formulation with the high rate (30 t/ha) produced the best outcomes for both soil and plant health. This amendment effectively enhanced all of the basil plant's properties, including SFW, SDW, PRL, RFW, RDW, SL, NL, NB, NF, chlorophyll content, essential oil content, and water content. Additionally, it improved the soil's physicochemical properties, acting as a biological vitality stimulator and maintaining suitable levels of HM. Its use as a fertilizer and amendment not only boosts production quality and productivity but also addresses soil problems and reduces the reliance on chemical fertilizers. In contrast, other treatment application rates appeared less effective then treatment T4 in achieving

a balanced nutrient supply, leading potentially to nutrient imbalances that impeded the optimal plant development. This study's results indicate that compost has the potential to serve as an alternative to chemical fertilizers, as it delivers comparable improvements in both plant and soil health.

According to the results of this study, organic compost can replace chemical fertilizers to achieve the highest yields and best soil quality. Compost serves multiple roles, enhancing plant productivity while improving the soil's chemical properties and physical attributes. Overall, this work indicates that, from an environmental perspective, the use of OAs derived from green waste helps to mitigate nutrient deficits, thereby reducing the environmental impact of biodegradable waste and promoting the concept of a circular economy.

In addition to evaluating yields, it is recommended to investigate the effect of varying compost application rates on the biological properties of the soil, as the relationships between the soil's biological properties and yield are well documented. These findings were obtained under greenhouse conditions; therefore, similar studies should be conducted in open fields to determine the effects in a natural setting.

Author Contributions: Conceptualization, M.O.L. and H.S.; methodology, M.O.L., H.S. and A.Z.; software, M.O.L. and H.S.; validation, M.O.L., L.M., M.M.A. and A.Z.; formal analysis, M.O.L., L.M., M.M.A., H.S. and A.Z.; resources, M.O.L., O.I.H., H.Y., K.M., A.Z. and R.M.; writing—original draft preparation, M.O.L., H.S., L.M. and A.Z.; writing—review and editing, M.O.L., H.S., L.M, M.M.A., O.I.H., H.Y., K.M., R.M. and A.Z.; visualization, M.O.L., H.S. and A.Z.; supervision, L.M., M.M.A. and A.Z.; funding acquisition, R.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the "MCGP" project (INRA and ICARDA) for their financial and technical support.

Data Availability Statement: All authors strongly encourage interested researchers to contact us, as we are more than willing to share the data upon request.

Acknowledgments: The authors extend their gratitude to those who contributed to this study, including the field sampling, laboratory analysis, and manuscript-writing teams from the Process Engineering and Environment Laboratory at the National Institute of Agricultural Research (INRA) and the International Center for Agricultural Research in the Dry Areas (ICARDA) in Morocco.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Khan, M.T.; Aleinikovienė, J.; Butkevičienė, L.-M. Innovative Organic Fertilizers and Cover Crops: Perspectives for Sustainable Agriculture in the Era of Climate Change and Organic Agriculture. *Agronomy* **2024**, *14*, 2871. [CrossRef]
2. Sanad, H.; Moussadek, R.; Mouhir, L.; Oueld Lhaj, M.; Dakak, H.; El Azhari, H.; Yachou, H.; Ghanimi, A.; Zouahri, A. Assessment of Soil Spatial Variability in Agricultural Ecosystems Using Multivariate Analysis, Soil Quality Index (SQI), and Geostatistical Approach: A Case Study of the Mnasra Region, Gharb Plain, Morocco. *Agronomy* **2024**, *14*, 1112. [CrossRef]
3. Tariq, A.; Graciano, C.; Sardans, J.; Zeng, F.; Hughes, A.C.; Ahmed, Z.; Ullah, A.; Ali, S.; Gao, Y.; Peñuelas, J. Plant Root Mechanisms and Their Effects on Carbon and Nutrient Accumulation in Desert Ecosystems under Changes in Land Use and Climate. *New Phytol.* **2024**, *242*, 916–934. [CrossRef] [PubMed]
4. Chew, K.W.; Chia, S.R.; Yen, H.-W.; Nomanbhay, S.; Ho, Y.-C.; Show, P.L. Transformation of Biomass Waste into Sustainable Organic Fertilizers. *Sustainability* **2019**, *11*, 2266. [CrossRef]
5. Ebbisa, A.F.; Dechassa, N.; Bekeko, Z.; Liben, F. Modifying Row-Configuration and Vermicompost Application Reduces Intercropped Peanut (*Arachis hypogaea* L.) Yield Instability and Penalty in Sorghum at Babile, Eastern Ethiopia. *Heliyon* **2024**, *10*, e35662. [CrossRef]
6. Manhou, K.; Moussadek, R.; Yachou, H.; Zouahri, A.; Douaik, A.; Hilal, I.; Ghanimi, A.; Hmouni, D.; Dakak, H. Assessing the Impact of Saline Irrigation Water on Durum Wheat (Cv. Faraj) Grown Sandy Clay Soils. *Agronomy* **2024**, *14*, 2865. [CrossRef]

7. Reichel, R.; Wei, J.; Islam, M.S.; Schmid, C.; Wissel, H.; Schröder, P.; Schloter, M.; Brüggemann, N. Potential of Wheat Straw, Spruce Sawdust, and Lignin as High Organic Carbon Soil Amendments to Improve Agricultural Nitrogen Retention Capacity: An Incubation Study. *Front. Plant Sci.* **2018**, *9*, 900. [CrossRef]
8. Cabanillas, C.; Stobbia, D.; Ledesma, A. Production and Income of Basil in and out of Season with Vermicomposts from Rabbit Manure and Bovine Ruminal Contents Alternatives to Urea. *J. Clean. Prod.* **2013**, *47*, 77–84. [CrossRef]
9. Damien Wassom, F.; Dakolé Daboy, C.; Meshuneké, A.; Elock Mbang, G.; Niemenak, N.; Annie Ewané, C. Effect of a Biological Compost Based on *Tithonia diversifolia* on the Growth of *Ocimum basilicum* L. *World J. Agric. Sci. Technol.* **2023**, *1*, 28–37. [CrossRef]
10. Masmoudi, S.; Magdich, S.; Rigane, H.; Medhioub, K.; Rebai, A.; Ammar, E. Effects of Compost and Manure Application Rate on the Soil Physico-Chemical Layers Properties and Plant Productivity. *Waste Biomass Valor.* **2020**, *11*, 1883–1894. [CrossRef]
11. Pandian, K.; Vijayakumar, S.; Mustaffa, M.R.A.F.; Subramanian, P.; Chitraputhirapillai, S. Biochar—A Sustainable Soil Conditioner for Improving Soil Health, Crop Production and Environment under Changing Climate: A Review. *Front. Soil Sci.* **2024**, *4*, 1376159. [CrossRef]
12. Kumar, S.S.; Wani, O.A.; Malik, A.R.; Kumar, S.; Patel, R. Biochar for Food Security and Environmental Sustainability Under Current Climate Change Scenario. In *Agricultural Diversification for Sustainable Food Production*; Babu, S., Singh, R., Rathore, S.S., Das, A., Singh, V.K., Eds.; Sustainability Sciences in Asia and Africa; Springer Nature: Singapore, 2024; pp. 59–88, ISBN 978-981-9775-16-3.
13. Jantamenchai, M.; Sukitprapanon, T.-S.; Tulaphitak, D.; Mekboonsonglarp, W.; Vityakon, P. Organic Phosphorus Forms in a Tropical Sandy Soil after Application of Organic Residues of Different Quality. *Geoderma* **2022**, *405*, 115462. [CrossRef]
14. Manimozhi, R.; Krishnamoorthy, G. Innovative Techniques in Agriculture: Transitioning From Traditional Farming to Precision and Hydroponic Agriculture. *Environ. Qual. Manag.* **2025**, *34*, e70047. [CrossRef]
15. Kim, H.N.; Park, J.H. Monitoring of Soil EC for the Prediction of Soil Nutrient Regime under Different Soil Water and Organic Matter Contents. *Appl. Biol. Chem.* **2024**, *67*, 1. [CrossRef]
16. Rekaby, S.A.; AL-Huqail, A.A.; Gebreel, M.; Alotaibi, S.S.; Ghoneim, A.M. Compost and Humic Acid Mitigate the Salinity Stress on Quinoa (*Chenopodium quinoa* Willd L.) and Improve Some Sandy Soil Properties. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 2651–2661. [CrossRef]
17. Gao, X.; Zhang, J.; Liu, G.; Kong, Y.; Li, Y.; Li, G.; Luo, Y.; Wang, G.; Yuan, J. Enhancing the Transformation of Carbon and Nitrogen Organics to Humus in Composting: Biotic and Abiotic Synergy Mediated by Mineral Material. *Bioresour. Technol.* **2024**, *393*, 130126. [CrossRef]
18. Kästner, M.; Miltner, A. Chapter 5-SOM and Microbes—What Is Left From Microbial Life. In *The Future of Soil Carbon*; Garcia, C., Nannipieri, P., Hernandez, T., Eds.; Academic Press: Cambridge, MA, USA, 2018; pp. 125–163. ISBN 978-0-12-811687-6.
19. Sarhan, M.; Shehata, A. Effect of Compost Along with Spraying of Methyl Jasmonate and Potassium Silicate on The Productivity of French Basil under Sandy Soil Conditions. *Egypt. J. Soil Sci.* **2023**, *63*, 225–241. [CrossRef]
20. Avramidou, P.; Evangelou, A.; Komilis, D. Use of Municipal Solid Waste Compost as a Growth Media for an Energy Plant (Rapeseed). *J. Environ. Manag.* **2013**, *121*, 152–159. [CrossRef]
21. Peng, G.; Zhang, T.; Lei, X.-Y.; Cui, X.-W.; Lu, Y.-X.; Fan, P.-F.; Long, S.-P.; Huang, J.; Gao, J.-S.; Zhang, Z.-H. Improvement of Soil Fertility and Rice Yield after Long-Term Application of Cow Manure Combined with Inorganic Fertilizers. *J. Integr. Agric.* **2023**, *22*, 2221–2232.
22. Das, S.; Jeong, S.T.; Das, S.; Kim, P.J. Composted Cattle Manure Increases Microbial Activity and Soil Fertility More Than Composted Swine Manure in a Submerged Rice Paddy. *Front. Microbiol.* **2017**, *8*, 1702. [CrossRef]
23. Sanad, H.; Mouhir, L.; Zouahri, A.; Moussadek, R.; El Azhari, H.; Yachou, H.; Ghanimi, A.; Oueld Lhaj, M.; Dakak, H. Assessment of Groundwater Quality Using the Pollution Index of Groundwater (PIG), Nitrate Pollution Index (NPI), Water Quality Index (WQI), Multivariate Statistical Analysis (MSA), and GIS Approaches: A Case Study of the Mnasra Region, Gharb Plain, Morocco. *Water* **2024**, *16*, 1263. [CrossRef]
24. Kravchenko, A.N.; Snapp, S.S.; Robertson, G.P. Field-Scale Experiments Reveal Persistent Yield Gaps in Low-Input and Organic Cropping Systems. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 926–931. [CrossRef] [PubMed]
25. Sulieman, A.M.E.; Abdallah, E.M.; Alanazi, N.A.; Ed-Dra, A.; Jamal, A.; Idriss, H.; Alshammari, A.S.; Shommo, S.A. Spices as Sustainable Food Preservatives: A Comprehensive Review of Their Antimicrobial Potential. *Pharmaceuticals* **2023**, *16*, 1451. [CrossRef]
26. Wahab, A.; Batool, F.; Muhammad, M.; Zaman, W.; Mikhlef, R.M.; Naeem, M. Current Knowledge, Research Progress, and Future Prospects of Phyto-Synthesized Nanoparticles Interactions with Food Crops under Induced Drought Stress. *Sustainability* **2023**, *15*, 14792. [CrossRef]
27. de Oliveira, I.; Chrysargyris, A.; Finimundy, T.C.; Carocho, M.; Santos-Buelga, C.; Calhelha, R.C.; Tzortzakis, N.; Barros, L.; Heleno, S.A. The Influence of Magnesium and Manganese Cations on the Chemical and Bioactive Properties of Purple and Green Basil. *Food Funct.* **2024**, *15*, 10644–10662. [CrossRef] [PubMed]

28. Jakovljević, D. Genetic Diversity, Cultivation, and Utilization of Aromatic Plants. In *Industrial Crops Improvement: Biotechnological Approaches for Sustainable Agricultural Development*; Kumar, N., Ed.; Springer Nature: Cham, Switzerland, 2025; pp. 171–182, ISBN 978-3-031-75937-6.
29. Damalas, C.A. Improving Drought Tolerance in Sweet Basil (*Ocimum basilicum*) with Salicylic Acid. *Sci. Hortic.* **2019**, *246*, 360–365. [CrossRef]
30. Sanad, H.; Oueld lhaj, M.; Zouahri, A.; Saafadi, L.; Dakak, H.; Mouhir, L. Groundwater Pollution by Nitrate and Salinization in Morocco: A Comprehensive Review. *J. Water Health* **2024**, *22*, 1756–1773. [CrossRef]
31. Sanad, H.; Moussadek, R.; Mouhir, L.; Lhaj, M.O.; Zahidi, K.; Dakak, H.; Manhou, K.; Zouahri, A. Ecological and Human Health Hazards Evaluation of Toxic Metal Contamination in Agricultural Lands Using Multi-Index and Geostatistical Techniques across the Mnasra Area of Morocco's Gharb Plain Region. *J. Hazard. Mater. Adv.* **2025**, *18*, 100724. [CrossRef]
32. Nocentini, M.; Mastrolonardo, G.; Michelozzi, M.; Cencetti, G.; Lenzi, A.; Panettieri, M.; Knicker, H.; Certini, G. Effects of Biochar and Compost Addition in Potting Substrates on Growth and Volatile Compounds Profile of Basil (*Ocimum basilicum* L.). *J. Sci. Food Agric.* **2024**, *104*, 1609–1620. [CrossRef]
33. Rastogi, M.; Verma, S.; Kumar, S.; Bharti, S.; Kumar, G.; Azam, K.; Singh, V. Soil Health and Sustainability in the Age of Organic Amendments: A Review. *Int. J. Environ. Clim. Change* **2023**, *13*, 2088–2102. [CrossRef]
34. Díaz-Pérez, F.J.; Díaz, R.; Valdés, G.; Valdebenito-Rolack, E.; Hansen, F. Effects of Microalgae and Compost on the Yield of Cauliflower Grown in Low Nutrient Soil. *Chil. J. Agric. Res.* **2023**, *83*, 181–194. [CrossRef]
35. Pagliarini, E.; Gaggìa, F.; Quartieri, M.; Toselli, M.; Di Gioia, D. Yield and Nutraceutical Value of Lettuce and Basil Improved by a Microbial Inoculum in Greenhouse Experiments. *Plants* **2023**, *12*, 1700. [CrossRef] [PubMed]
36. Ashoka, P.; Saikanth, D.; Verma, P. Organic Agriculture: A Sustainable Solution for a Healthy Future. In *Advanced Farming Technology*; Scripown Publications: Delhi, India, 2023; p. 122.
37. Mohanty, L.K.; Singh, N.; Raj, P.; Prakash, A.; Tiwari, A.K.; Singh, V.; Sachan, P. Nurturing Crops, Enhancing Soil Health, and Sustaining Agricultural Prosperity Worldwide through Agronomy. *J. Exp. Agric. Int.* **2024**, *46*, 46–67. [CrossRef]
38. Nakachew, K.; Gelaye, Y.; Ali, S.; Gebeyehu, T.; Eskezia, A. Exploring the Application of Zeolite Technology in Ethiopia: A Path to Sustainable Agriculture Development. *J. Plant Nutr. Soil Sci.* **2025**, *188*, 17–30. [CrossRef]
39. Juncal, M.J.L.; Masino, P.; Bertone, E.; Stewart, R.A. Towards Nutrient Neutrality: A Review of Agricultural Runoff Mitigation Strategies and the Development of a Decision-Making Framework. *Sci. Total Environ.* **2023**, *874*, 162408. [CrossRef]
40. Novak, J.M.; Watts, D.W.; Sigua, G.C.; Ducey, T.F. Corn Grain and Stover Nutrient Uptake Responses from Sandy Soil Treated with Designer Biochars and Compost. *Agronomy* **2021**, *11*, 942. [CrossRef]
41. Mwendwa, S. Revisiting Soil Texture Analysis: Practices towards a More Accurate Bouyoucos Method. *Heliyon* **2022**, *8*, e09395. [CrossRef]
42. Oueld Lhaj, M.; Moussadek, R.; Mouhir, L.; Mdarhri Alaoui, M.; Sanad, H.; Iben Halima, O.; Zouahri, A. Assessing the Evolution of Stability and Maturity in Co-Composting Sheep Manure with Green Waste Using Physico-Chemical and Biological Properties and Statistical Analyses: A Case Study of Botanique Garden in Rabat, Morocco. *Agronomy* **2024**, *14*, 1573. [CrossRef]
43. Kheir, A.M.S.; Govind, A.; Zoghdan, M.G.; Khalifa, T.H.; Aboelsoud, H.M.; Shabana, M.M.A. The Fusion Impact of Compost, Biochar, and Polymer on Sandy Soil Properties and Bean Productivity. *Agronomy* **2023**, *13*, 2544. [CrossRef]
44. Kim, S.Y.; Lee, J.J.; Lee, G. Comparative Efficacies of Iron Oxide-Modified Biochar and Pyrite-Modified Biochar for Simultaneous Passivation of Cadmium and Arsenic in Aqueous Solutions and Lettuce (*Lactuca sativa*. L) Cultivation. *Appl. Biol. Chem.* **2025**, *68*, 13. [CrossRef]
45. Sewpersad, T.; Xulu, S.; Gebreslasie, M. The Assessment of Soil Organic Matter in the KwaZulu-Natal Province of South Africa and Its Relationship to Spectroscopy Data. *Geocarto Int.* **2024**, *39*, 2361702. [CrossRef]
46. Abu El Haija, K.; Chiang, Y.W.; Santos, R.M. On-Site Determination of Soil Organic Carbon Content: A Photocatalytic Approach. *Clean Technol.* **2024**, *6*, 784–801. [CrossRef]
47. Nelson, J.T.; Adjuik, T.A.; Moore, E.B.; VanLoocke, A.D.; Ramirez Reyes, A.; McDaniel, M.D. A Simple, Affordable, Do-It-Yourself Method for Measuring Soil Maximum Water Holding Capacity. *Commun. Soil Sci. Plant Anal.* **2024**, *55*, 1190–1204. [CrossRef]
48. Huang, Y.; Xiong, T.; Zhao, M.; Deng, Y.; Yang, G.; Ban, Y.; Lei, T.; Yu, X.; Huang, Y. Influence of Soil Properties and Near-Surface Roots on Soil Infiltration Process in Short-Rotation Eucalyptus Plantations in Southern Subtropical China. *CATENA* **2024**, *234*, 107606. [CrossRef]
49. Tebeje, A.K.; Abebe, W.B.; Hussein, M.A.; Mhiret, D.A.; Zimale, F.A.; Desta, G.; Assefa, T.T.; Tilahun, S.A.; Ahmed, M.A. Dynamics of Soil Quality in a Conserved Landscape in the Highland Sub Humid Ecosystem, Northwestern Ethiopia. *Front. Sustain. Food Syst.* **2024**, *8*, 1270265. [CrossRef]
50. Rasa, K.; Tähtikarhu, M.; Miettinen, A.; Kähärä, T.; Uusitalo, R.; Mikkola, J.; Hyväluoma, J. A Large One-Time Addition of Organic Soil Amendments Increased Soil Macroporosity but Did Not Affect Intra-Aggregate Porosity of a Clay Soil. *Soil Tillage Res.* **2024**, *242*, 106139. [CrossRef]

51. Aydi, S.; Sassi Aydi, S.; Rahmani, R.; Bouaziz, F.; Souchard, J.P.; Merah, O.; Abdelly, C. Date-Palm Compost as Soilless Substrate Improves Plant Growth, Photosynthesis, Yield and Phytochemical Quality of Greenhouse Melon (*Cucumis melo* L.). *Agronomy* **2023**, *13*, 212. [CrossRef]
52. Zhang, X.; Warren, C.J.; Spiers, G.; Voroney, P. Comparison of the Integral Suspension Pressure (ISP) and the Hydrometer Methods for Soil Particle Size Analysis. *Geoderma* **2024**, *442*, 116792. [CrossRef]
53. Ud Din, M.M.; Khan, M.I.; Azam, M.; Ali, M.H.; Qadri, R.; Naveed, M.; Nasir, A. Effect of Biochar and Compost Addition on Mitigating Salinity Stress and Improving Fruit Quality of Tomato. *Agronomy* **2023**, *13*, 2197. [CrossRef]
54. González-Espíndola, L.Á.; Pedroza-Sandoval, A.; Trejo-Calzada, R.; Jacobo-Salcedo, M.D.R.; García De Los Santos, G.; Quezada-Rivera, J.J. Relative Water Content, Chlorophyll Index, and Photosynthetic Pigments on *Lotus corniculatus* L. in Response to Water Deficit. *Plants* **2024**, *13*, 961. [CrossRef]
55. Perbellini, A.; Pelloso, F.; Grigolato, S.; Zanchin, A.; Guerrini, L. Evaluation of Fractions Obtained Through Steam Distillation and Hydroalcoholic Maceration of Wood Chips from *Pinus mugo* for Flavouring Italian Spirit *grappa*. *Beverages* **2025**, *11*, 14. [CrossRef]
56. Souri, M.K.; Hatamian, M.; Tesfamariam, T. Plant Growth Stage Influences Heavy Metal Accumulation in Leafy Vegetables of Garden Cress and Sweet Basil. *Chem. Biol. Technol. Agric.* **2019**, *6*, 25. [CrossRef]
57. Rajendiran, D.; Harikrishnan, N.; Veeramuthu, K. Heavy Metal Concentrations and Pollution Indicators in the Ennore Ecosystem, East Coast of Tamilnadu, India Using Atomic Absorption Spectrometry Study with Statistical Approach. *Sci. Rep.* **2025**, *15*, 9161. [CrossRef] [PubMed]
58. Atta, M.I.; Zehra, S.S.; Dai, D.-Q.; Ali, H.; Naveed, K.; Ali, I.; Sarwar, M.; Ali, B.; Iqbal, R.; Bawazeer, S.; et al. Amassing of Heavy Metals in Soils, Vegetables and Crop Plants Irrigated with Wastewater: Health Risk Assessment of Heavy Metals in Dera Ghazi Khan, Punjab, Pakistan. *Front. Plant Sci.* **2023**, *13*, 1080635. [CrossRef]
59. Pan, S.; Liu, Z.; Han, Y.; Zhang, D.; Zhao, X.; Li, J.; Wang, K. Using the Pearson's Correlation Coefficient as the Sole Metric to Measure the Accuracy of Quantitative Trait Prediction: Is It Sufficient? *Front. Plant Sci.* **2024**, *15*, 1480463. [CrossRef]
60. Li, R.; Tao, R.; Ling, N.; Chu, G. Chemical, Organic and Bio-Fertilizer Management Practices Effect on Soil Physicochemical Property and Antagonistic Bacteria Abundance of a Cotton Field: Implications for Soil Biological Quality. *Soil Tillage Res.* **2017**, *167*, 30–38. [CrossRef]
61. Francioli, D.; Schulz, E.; Lentendu, G.; Wubet, T.; Buscot, F.; Reitz, T. Mineral vs. Organic Amendments: Microbial Community Structure, Activity and Abundance of Agriculturally Relevant Microbes Are Driven by Long-Term Fertilization Strategies. *Front. Microbiol.* **2016**, *7*, 1446. [CrossRef]
62. Sanad, H.; Moussadek, R.; Dakak, H.; Zouahri, A.; Oueld Lhaj, M.; Mouhir, L. Ecological and Health Risk Assessment of Heavy Metals in Groundwater within an Agricultural Ecosystem Using GIS and Multivariate Statistical Analysis (MSA): A Case Study of the Mnasra Region, Gharb Plain, Morocco. *Water* **2024**, *16*, 2417. [CrossRef]
63. Sundberg, C.; Yu, D.; Franke-Whittle, I.; Kauppi, S.; Smårs, S.; Insam, H.; Romantschuk, M.; Jönsson, H. Effects of pH and Microbial Composition on Odour in Food Waste Composting. *Waste Manag.* **2013**, *33*, 204–211. [CrossRef]
64. El-Akhdar, I.; Shabana, M.M.A.; El-Khateeb, N.M.M.; Elhawat, N.; Alshaal, T. Sustainable Wheat Cultivation in Sandy Soils: Impact of Organic and Biofertilizer Use on Soil Health and Crop Yield. *Plants* **2024**, *13*, 3156. [CrossRef]
65. Liang, B.; Yang, X.; He, X.; Murphy, D.V.; Zhou, J. Long-Term Combined Application of Manure and NPK Fertilizers Influenced Nitrogen Retention and Stabilization of Organic C in Loess Soil. *Plant Soil* **2012**, *353*, 249–260. [CrossRef]
66. Cannavo, P.; Herbreteau, A.; Juret, D.; Martin, M.; Guénon, R. Short-term Effects of Food Waste Composts on Physicochemical Soil Quality and Horticultural Crop Production. *J. Plant Nutr. Soil Sci.* **2024**, *188*, 31–44. [CrossRef]
67. Kwiatkowska-Malina, J. Qualitative and Quantitative Soil Organic Matter Estimation for Sustainable Soil Management. *J. Soils Sediments* **2018**, *18*, 2801–2812. [CrossRef]
68. Gautam, A.; Guzman, J.; Kovacs, P.; Kumar, S. Manure and Inorganic Fertilization Impacts on Soil Nutrients, Aggregate Stability, and Organic Carbon and Nitrogen in Different Aggregate Fractions. *Arch. Agron. Soil Sci.* **2022**, *68*, 1261–1273. [CrossRef]
69. Yazdanpanah, N.; Mahmoodabadi, M.; Cerdà, A. The Impact of Organic Amendments on Soil Hydrology, Structure and Microbial Respiration in Semiarid Lands. *Geoderma* **2016**, *266*, 58–65. [CrossRef]
70. Gerke, J. The Central Role of Soil Organic Matter in Soil Fertility and Carbon Storage. *Soil Syst.* **2022**, *6*, 33. [CrossRef]
71. Al-Suhaibani, N.; Selim, M.; Alderfasi, A.; El-Hendawy, S. Comparative Performance of Integrated Nutrient Management between Composted Agricultural Wastes, Chemical Fertilizers, and Biofertilizers in Improving Soil Quantitative and Qualitative Properties and Crop Yields under Arid Conditions. *Agronomy* **2020**, *10*, 1503. [CrossRef]
72. Agegnehu, G.; vanBeek, C.; Bird, M.I. Influence of Integrated Soil Fertility Management in Wheat and Tef Productivity and Soil Chemical Properties in the Highland Tropical Environment. *J. Soil Sci. Plant Nutr.* **2014**, *14*, 532–545. [CrossRef]
73. Oueld Lhaj, M.; Moussadek, R.; Zouahri, A.; Sanad, H.; Saafadi, L.; Mdarhri Alaoui, M.; Mouhir, L. Sustainable Agriculture Through Agricultural Waste Management: A Comprehensive Review of Composting's Impact on Soil Health in Moroccan Agricultural Ecosystems. *Agriculture* **2024**, *14*, 2356. [CrossRef]

74. Ozlu, E.; Kumar, S. Response of Soil Organic Carbon, pH, Electrical Conductivity, and Water Stable Aggregates to Long-Term Annual Manure and Inorganic Fertilizer. *Soil Sci. Soc. Am. J.* **2018**, *82*, 1243–1251. [CrossRef]
75. Kavdır, Y.; İşler, N. Effect of Compost Addition on Porosity and Hydraulic Properties of Different Textured Soils. *J. Adv. Res. Nat. Appl. Sci.* **2024**, *10*, 833–844. [CrossRef]
76. Reynolds, W.D.; Nurse, R.E.; Phillips, L.A.; Drury, C.F.; Yang, X.M.; Page, E.R. Characterizing Mass–Volume–Density–Porosity Relationships in a Sandy Loam Soil Amended with Compost. *Can. J. Soil Sci.* **2020**, *100*, 289–301. [CrossRef]
77. Das, S.K.; Ghosh, G.K.; Avasthe, R. Biochar Application for Environmental Management and Toxic Pollutant Remediation. *Biomass Convers. Biorefinery* **2023**, *13*, 555–566. [CrossRef]
78. Dincă, L.C.; Grenni, P.; Onet, C.; Onet, A. Fertilization and Soil Microbial Community: A Review. *Appl. Sci.* **2022**, *12*, 1198. [CrossRef]
79. Liu, W.; Yang, Z.; Ye, Q.; Peng, Z.; Zhu, S.; Chen, H.; Liu, D.; Li, Y.; Deng, L.; Shu, X.; et al. Positive Effects of Organic Amendments on Soil Microbes and Their Functionality in Agro-Ecosystems. *Plants* **2023**, *12*, 3790. [CrossRef]
80. Song, D.; Dai, X.; Guo, T.; Cui, J.; Zhou, W.; Huang, S.; Shen, J.; Liang, G.; He, P.; Wang, X.; et al. Organic Amendment Regulates Soil Microbial Biomass and Activity in Wheat-Maize and Wheat-Soybean Rotation Systems. *Agric. Ecosyst. Environ.* **2022**, *333*, 107974. [CrossRef]
81. Manhou, K.; Mouna, T.; Moussadek, R.; Zouahri, A.; Ghanimi, A.; Sanad, H.; Lhaj, M.O.; Hmouni, D.; Dakak, H. Genetic Diversity and Performance of Durum Wheat (*Triticum turgidum* L. ssp. Durum Desf.) Germplasm Based on Agro-Morphological and Quality Traits: Experimentation and Statistical Analysis. *Preprints* **2025**. [CrossRef]
82. Abd-Elhalim, B.; Gideon, M.; Kuzmin, A.; Boyi, M. Impact of Dumpsite Compost on Heavy Metal Accumulation in Some Cultivated Plants. *BMC Res. Notes* **2025**, *18*, 20. [CrossRef]
83. Adagunodo, T.A.; Sunmonu, L.A.; Emetere, M.E. Heavy Metals' Data in Soils for Agricultural Activities. *Data Brief* **2018**, *18*, 1847–1855. [CrossRef]
84. Ahmad, K.; Ashfaq, A.; Khan, Z.I.; Ashraf, M.; Akram, N.A.; Yasmin, S.; Batool, A.I.; Sher, M.; Shad, H.A.; Khan, A.; et al. Health Risk Assessment of Heavy Metals and Metalloids via Dietary Intake of a Potential Vegetable (*Coriandrum sativum* L.) Grown in Contaminated Water Irrigated Agricultural Sites of Sargodha, Pakistan. *Hum. Ecol. Risk Assess. Int. J.* **2016**, *22*, 597–610. [CrossRef]
85. Khan, Z.I.; Haider, R.; Ahmad, K.; Nadeem, M.; Ashfaq, A.; Alrefaei, A.F.; Almutairi, M.H.; Mehmood, N.; Batool, A.I.; Memona, H.; et al. Evaluation of Cu, Zn, Fe, and Mn Concentrations in Water, Soil, and Fruit Samples in Sargodha District, Pakistan. *Sustainability* **2023**, *15*, 15696. [CrossRef]
86. Ogunlana, R.; Korode, A.I.; Ajibade, Z.F. Assessing the Level of Heavy Metals Concentration in Soil around Transformer at Akoko Community of OndoState, Nigeria. *J. Appl. Sci. Environ. Manag.* **2020**, *24*, 2183–2189. [CrossRef]
87. Genua, F.; Lancellotti, I.; Leonelli, C. Geopolymer-Based Stabilization of Heavy Metals, the Role of Chemical Agents in Encapsulation and Adsorption: Review. *Polymers* **2025**, *17*, 670. [CrossRef] [PubMed]
88. Ahmed, N.; Zhang, B.; Chachar, Z.; Li, J.; Xiao, G.; Wang, Q.; Hayat, F.; Deng, L.; Narejo, M.-N.; Bozdar, B.; et al. Micronutrients and Their Effects on Horticultural Crop Quality, Productivity and Sustainability. *Sci. Hortic.* **2024**, *323*, 112512. [CrossRef]
89. Wieczorek, J.; Baran, A.; Bubak, A. Mobility, Bioaccumulation in Plants, and Risk Assessment of Metals in Soils. *Sci. Total Environ.* **2023**, *882*, 163574. [CrossRef]
90. Mylavarapu, R.S.; Zinati, G.M. Improvement of Soil Properties Using Compost for Optimum Parsley Production in Sandy Soils. *Sci. Hortic.* **2009**, *120*, 426–430. [CrossRef]
91. Abdelfattah, M.A.; Rady, M.M.; Belal, H.E.E.; Belal, E.E.; Al-Qthanin, R.; Al-Yasi, H.M.; Ali, E.F. Revitalizing Fertility of Nutrient-Deficient Virgin Sandy Soil Using Leguminous Biocompost Boosts *Phaseolus vulgaris* Performance. *Plants* **2021**, *10*, 1637. [CrossRef]
92. Akhtar, M.S.; Hameed, A.; Aslam, S.; Ullah, R.; Kashif, A. Phytoremediation of Metal-Contaminated Soils and Water in Pakistan: A Review. *Water Air Soil Pollut.* **2022**, *234*, 11. [CrossRef]
93. Voca, H.; Piscitelli, L.; Mezzapesa, G.N.; Mondelli, D.; Miano, T.; D'Orazio, V. Biochar Effect on Crop Performance and Pb and Zn Uptake of Tomato (*Solanum lycopersicum*, L.) Plants Grown on Heavy Metals Contaminated Kosovo Soils. *J. Environ. Sci. Health Part B* **2020**, *55*, 844–853. [CrossRef]
94. Aithani, D.; Kushawaha, J. Heavy Metals Contamination in Environment. In *Remediation of Heavy Metals*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2024; pp. 15–30. ISBN 978-1-119-85358-9.
95. Ladha, J.K.; Jat, M.L.; Stirling, C.M.; Chakraborty, D.; Pradhan, P.; Krupnik, T.J.; Sapkota, T.B.; Pathak, H.; Rana, D.S.; Tesfaye, K.; et al. Chapter Two—Achieving the Sustainable Development Goals in Agriculture: The Crucial Role of Nitrogen in Cereal-Based Systems. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2020; Volume 163, pp. 39–116.

96. Ansar, A.; Du, J.; Javed, Q.; Adnan, M.; Javaid, I. Biodegradable Waste in Compost Production: A Review of Its Economic Potential. *Nitrogen* **2025**, *6*, 24. [CrossRef]
97. De Corato, U. Agricultural Waste Recycling in Horticultural Intensive Farming Systems by On-Farm Composting and Compost-Based Tea Application Improves Soil Quality and Plant Health: A Review under the Perspective of a Circular Economy. *Sci. Total Environ.* **2020**, *738*, 139840. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.