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Agronomic performance of sheep manure–enriched municipal solid waste compost for red beetroot cultivation (Gharb region, Morocco)

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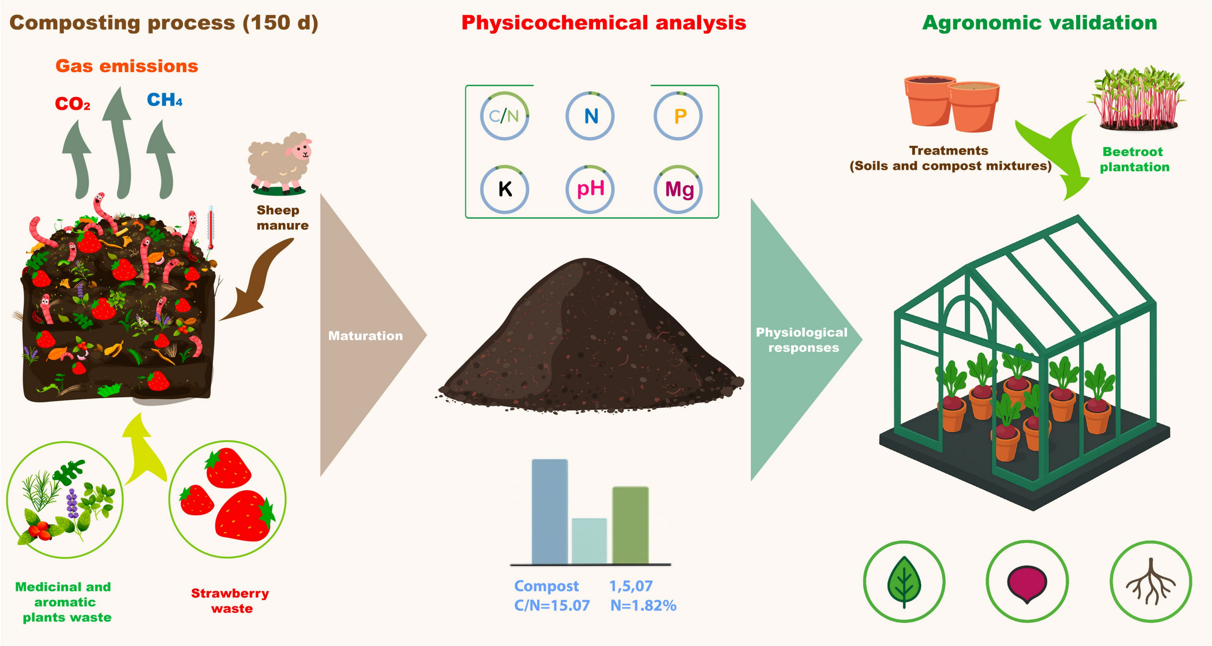
Industrial waste poses a major challenge in Morocco and worldwide, as its increasing production presents significant environmental concerns. In Morocco, approximately 1.6 million tonnes of industrial waste are generated annually, with a considerable portion classified as hazardous, primarily from the agri-food, chemical, and construction sectors. These wastes contribute substantially to greenhouse gas emissions and the deterioration of soil and water quality, acting as a barrier to sustainable management. In this context, composting strategy emerges as a promising method for the valorization of organic waste. This study focuses on the formulation of compost derived from the industrial waste of medicinal and aromatic plants (EDEPAM company), combined with agro-industrial waste (strawberry), and supplemented with sheep manure to correct nitrogen deficiencies. After 150 days of composting followed by 30 days of maturation, the final product showed stable and favorable physicochemical characteristics [Nitrogen (1.82%), C/N ratio (15.07), pH (7.94)], while maintaining a high organic matter content. The agronomic validation was conducted in greenhouse conditions on beetroot (*Beta vulgaris L.*) grown in two contrasting soil types (Fluvisol and Vertisol), revealing a significant improvement in growth and photosynthetic performance at moderate application rates (25% of compost). These findings highlight the potential of integrating compost to enhance both crop yields and soil quality, thereby supporting sustainable and locally adapted agricultural practices.

KEYWORDS

circular economy, composting, sheep manure, soil management, sustainable agriculture, waste management

1 Introduction

Due to rapid urbanization and population growth, waste management has emerged as a critical global challenge over the last few decades, with over 2 billion tons of solid waste generated annually, projected to increase by 70% by 2050 (Kaza et al., 2018). Among this waste, the organic fraction constitutes approximately 60%, highlighting the urgent need for effective



GRAPHICAL ABSTRACT

management strategies (Awasthi et al., 2021). These organic wastes not only contribute significantly to greenhouse gas emissions, estimated at 3.3 billion tons per year, but also accelerate ecosystem degradation and can lead to public health issues (Zhang et al., 2021). The global food system alone accounts for about 1.3 billion tons of food waste each year, which could be redirected towards recovery and composting initiatives (Ng and Wong, 2024). Composting is a promising solution to mitigate these challenges (Ayilara et al., 2020). It not only recycles organic materials but also can enrich soil fertility and structure, reducing dependency on chemical fertilizers and improving agricultural sustainability (Oueld Lhaj et al., 2025).

In Morocco, the situation follows the global trends, with municipal solid waste (MSW) quantity reaching 6.85 million metric tons annually (Kaza et al., 2018). To address this, Morocco has implemented strategic reforms, including Solid Waste Management Law 28-00 and the National Municipal Solid Waste Management Program (PNDM) adopted in 2006 and 2008, respectively, to enhance governance and sustainability in waste management practices (Louzizi et al., 2025). Recently, Morocco launched the National Municipal Solid Waste Recovery Program (PNVDM), supported by a US$250 million World Bank-backed program, aiming to improve MSW financial & environmental performance (including upgrading landfills, enhancing recycling, and closing uncontrolled dumpsites) under stronger governance and policy reforms (World Bank, 2024).

The potential for valorizing organic waste from industries related to medicinal and aromatic plants, as well as fruit processing, is particularly promising. These sectors generate significant amounts of organic waste that are often underestimated, such as biomass from the hydrodistillation of essential oils from plants like rosemary (*Rosmarinus officinalis*), which can be composted (Greff et al., 2021). Using this waste not only reduces landfill dependency but also enriches compost with valuable nutrients, enhancing soil health (Noor et al., 2021). In Morocco, where agricultural practices are prevalent, the management of fruit and plant waste remains inadequate, presenting an opportunity for the adoption of sustainable agricultural practices (Bendaoud et al., 2022). Additionally, integrating sheep manure into the composting process offers numerous benefits due to its high nitrogen (N) content, which improves compost quality and accelerates decomposition (Ebrahimi and Asadi, 2019). This practice also enhances microbial diversity and accelerates the breakdown of organic materials while aligning with sustainable agricultural principles by recycling nutrients back into the soil (Xie et al., 2025).

From an agricultural point of view, compost application has been shown to significantly enhance the growth and yield of different crops such as Beetroot (*Beta vulgaris L.*) (Majhi et al., 2024), tomato (*Solanum lycopersicum*) (Cozzolino et al., 2023), Citrus (Castellano-Hinojosa et al., 2023), etc. Previous studies have shown that compost can enhance various growth parameters, including plant height, leaf number, and root size. For instance, studies have demonstrated that beetroot plants treated with compost exhibited greater height than control groups, along with increased root yields and larger diameters (Mupambwa and Mnkeni, 2018; Adekiya et al., 2019). The benefits of compost are attributed to its ability to enrich the soil with essential nutrients, such as phosphorus (P), which promotes root development and enhances nutrient absorption (Majhi et al., 2024).

This research presents an experimental study focused on formulating compost from different available organic wastes in Morocco (rosemary waste from the hydrodistillation industry, sheep manure and strawberry residues from a fruit export company) and evaluating its impact on beetroot during an agronomic trial. The potential of this work lies in the valorization of large quantities of waste produced daily, which currently lack proper management strategies, negatively affecting the entire ecosystem in Morocco.

2 Materials and methods

2.1 Research methodology and importance of the study

A bibliometric analysis (Figure 1) was carried out using Scopus database (TITLE-ABS-KEY, last searched on [2 September 2025]) with the query "composting" AND "sheep manure," yielding 197 published documents. When adding "agriculture," this number dropped to just 30 documents, suggesting that while composting sheep manure is fairly well researched, relatively few studies reached agronomic applications. Most focus on chemical, process, or environmental aspects rather than agricultural validation. On the other hand, when searching using the query "composting" AND "aromatic plants waste" OR "medicinal plants waste" resulted in 5 research papers, while when adding the keyword "agriculture," no results were found. The search covers the last 20 years and reveals a notable gap: few experiments reached the agronomic test stage. Illustratively, a study on food waste composting (Lim et al., 2022) found keywords such as *"soil," "plant," "application,"* strongly linked, implying a broader direction that compost research must reach experiment validation, but often does not. This highlights a research

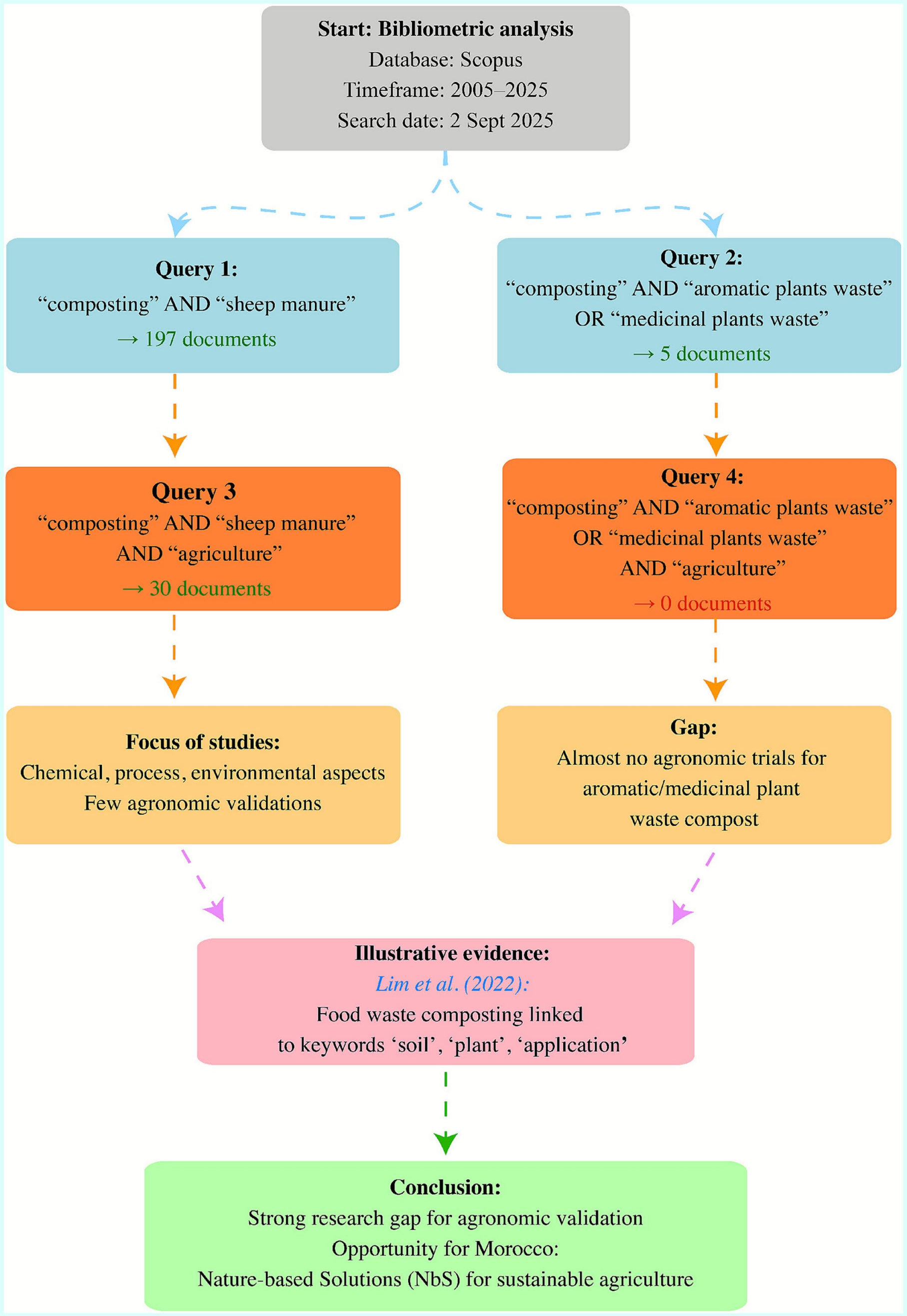


FIGURE 1
Flow diagram of research methodology.

opportunity for field-scale or crop-level valorization of these types of waste into valuable compost, especially in Morocco, where nature-based solutions (NbS) are needed to strengthen sustainable agriculture. Therefore, this study is considered important regarding filling this gap with new findings.

2.2 Experimental design and compost formulation

The composting samples were obtained from the hydrodistillation company of aromatic and medicinal plants (EDEPAM). The plant covers an area of 7,200 m^2 and discharges 5 to 6 tons/day of solid organic waste. The compost was prepared using a mixture of industrial and agro-industrial organic residues collected from two sources: the essential oil hydrodistillation plant and a red fruit processing company. The initial formulation consisted of 80% hydrodistillation residues and 20% strawberry agro-industrial residues, reflecting both the availability of these materials, their complementary nutrient profiles, and the objective of the EDEPAM plant to valorize and compost a large quantity of its generated residues. The selection of this proportion is supported by previous studies demonstrating that combining high-carbon industrial residues with nitrogen-rich organic wastes optimizes the C/N ratio, promotes microbial activity, and enhances compost maturation (Azim et al., 2018; Greff et al., 2021; Ebrahimi and Asadi, 2019).

The composting process took place over a period of 150 days, in a pile with dimensions of 6 m in length, 3 m in width and 1.5 m in height. To ensure significant microbial metabolic activity, water was added to reach an optimal moisture content of 60%, and oxygen was supplied by manual turning once a week. The temperature of the compost was also measured twice a week using a manual digital thermometer (Ludwig Schneider 12,200, Germany). For physicochemical analyses, a representative sample of 1 kg was taken from different areas of the compost (center, surface, core, and sides) at the end of the composting process, i.e., after 150 days. The samples were ground and sieved using a 2 mm sieve. Due to the low N content of the compost, a quantity of sheep manure was added, along with compost, in the following proportion (60% compost and 40% sheep manure). The mixture was monitored for temperature twice a week and turned once a week for 30 days. Moisture was checked and maintained at 60–70% throughout the process to ensure and support microbial activity. In parallel, another amendment using a commercial fertilizer (Yara Mila HYDROCOMPLEX Partner) was added to the initial compost without sheep manure. The analyses were done on the three compost mixtures and are presented and discussed in the results section below.

2.3 Physicochemical analysis of feedstocks

A series of physicochemical analyses was conducted, and organic matter (OM) content was determined by evaluating the difference between dry mass and mass after calcination (Navarro et al., 1993). Chemical oxygen demand (COD) was estimated using the colorimetric method (Knechtel, 1978; Lamssali et al., 2024); the C/N ratio was calculated by dividing the total organic carbon (TOC) value by Total Kjeldahl Nitrogen (TKN). Potassium (K), P, calcium (Ca), and zinc (Zn) were quantified by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (Olesik, 1991). The pH and electrical conductivity (EC) were measured on a 1 g sample diluted in 10 mL distilled water, according to French standard AFNOR NFT 90-015 (AFNOR, 1975). TOC and TKN were evaluated as described by Tallou et al. (2020).

2.4 Phytotoxicity test

The phytotoxicity of the compost was evaluated using a germination test, a common method because of its simplicity and reliability. This test enables the observation of the effect of compost on seed germination and seedling development, identifying potential inhibitory substances or, conversely, those that are favorable to plant growth.

An aqueous compost extract was prepared at a ratio of 1:10 (weight/volume), mixing 10 g of sieved compost with 100 mL of distilled water. The suspension was stirred for 1 h at room temperature, then left to stand for 30 min. After sedimentation, the extract was filtered through Whatman no. 1 filter paper to obtain a clear filtrate. Then, the seeds used for the germination test were chosen for their sensitivity to phytotoxic substances. The selected seed species used in this study were tomato (*Solanum lycopersicum*) and lettuce (*Lactuca sativa*), known for their responsiveness to inhibitory compounds that may be present in compost. After that, Petri dishes were lined with sterile filter paper, then moistened with 5 mL of compost extract. A control was performed using only distilled water. In each dish, 20 seeds were placed, then covered and kept in a controlled environment at 25 °C, in darkness for 72 h to promote germination. After incubation, the germination percentage (%) which is the number of seeds germinated relative to the total number of seeds, radicle length (mm), and the germination index (GI) calculated as:

$$GI = (GC / GT) \times (LC / LT) \times 100 \tag{1}$$

where GC is the number of seeds germinated in the compost extract, GT in the control, LC is the root length in the extract, and LT is the root length in the control. For lettuce seeds, the GI obtained was 133.25%, while for tomatoes, GI reached 113.1%, showing that the compost is mature and can be used in the agronomic test on beetroot.

2.5 Agronomic test and fruit quality analysis

2.5.1 Experimental design and agronomic validation of compost

2.5.1.1 Agronomic test scenario

The Gharb region, a major agricultural hub in northwestern Morocco, was selected for this study due to its two contrasting soil types according to the WRB classification: Fluvisol (sandy loam soil) and a Vertisol (clay-rich soil). These soils are representative of the region's cultivated lands and allow assessment of compost efficacy under different pedological conditions (Bendaoud et al., 2022). The experiment was carried out in a greenhouse at the Faculty of Sciences, Ibn Tofail University, Kenitra, starting on April 1, 2024, to evaluate the effect of different mixtures of compost on two soil types (Fluvisol and Vertisol) and on the germination, growth, and biomass production of beetroot (*Beta vulgaris L.*). Seeds of the variety "Plat d'Égypte" (standard, untreated, lot no. 880102) were used, and their viability was confirmed using the International Seed Testing Association (ISTA) standard for germination test. Eight substrate mixtures were prepared (v/v), homogenized, and sieved to a particle size of ≤2 mm before being filled into pots of 2–3 L capacity. For each treatment, three repetitions were performed, where the control contained 100% Fluvisol (S) and 100% Vertisol (T). Then, a mixture of 25, 50, and 75% compost (C) was established, as summarized in Figure 2. The experiment followed a systematic block design without randomization. Germination was first conducted in alveolar trays at a density of two seeds per cell. Emergence was recorded on day 3 (d3) and day 10 (d10), after which seedlings were thinned to one per cell at the two true-leaf stage. Transplanting was performed at the 2–3 true-leaf stage, with one seedling per pot transferred with its intact root ball into pre-moistened and lightly compacted soil. Irrigation was applied gravimetrically to maintain a constant pot weight, and the volumes of water supplied were recorded. During the experiment, no fertilizer was added to assess the effect of compost. Plants were protected against water and thermal stress during the first 72 h following transplantation. Measurements included germination percentage (J3, J10) and T50, weekly growth (leaf number and mortality), and final harvest on July 16, 2024, where the fresh weight of fruits, roots and leaves was determined and for each treatment, three replicates were adopted.

2.5.1.2 Chlorophyll index and fluorescence

Chlorophyll content was estimated non-destructively using a FieldScout CM 1000 Chlorophyll Meter (Spectrum Technologies Inc., United States). The instrument measures the ratio of near-infrared (NIR) to red reflectance and provides a Chlorophyll Index (CI). Chlorophyll fluorescence was measured using a portable fluorometer (OS30p+, Opti-Sciences, United States). Fully expanded leaves were dark-adapted for 20 min prior to measurement. The instrument recorded the minimum fluorescence (Fo), maximum fluorescence (Fm), and variable fluorescence (Fv = Fm − Fo). From these parameters, the maximum quantum efficiency of PSII photochemistry (Fv/Fm) was calculated. Three fully expanded leaves per plant were measured, and values were averaged to obtain a representative index for each replicate (Chlorophyll and fluorescence). Chlorophyll and fluorescence measurements were conducted to assess the physiological status and photosynthetic efficiency of beetroot. These indicators enabled us to assess plant response and potential stress under different compost treatments.

2.5.1.3 Soil analysis

Two types of soil were used in this study to assess the impact of compost on beetroot, with their physicochemical properties and fertility status analyzed: a Fluvisol soil and Moroccan Vertisol (Tirs), a clay-rich soil. Generally, Vertisols are fertile soils known worldwide, and in Morocco they are considered critical agricultural soils with high productive value (Moussadek et al., 2017). Soil analysis was conducted to characterize the physicochemical properties of the soil used in this study. For mineral N determination, 20 g of soil were weighed into 250 mL flasks, and 200 mL of 2 N KCl solution was added. The suspensions were shaken for one h on a reciprocal shaker, then filtered through Whatman filter paper into 250 mL Erlenmeyer flasks. The filtrates were analyzed using a Kjeldahl-type steam distillation apparatus. To determine ammonium (NH_4^+), 50 mL of the soil extract were transferred into a digestion tube, to which 1 g of magnesium oxide (MgO) was added. The released NH_3 was collected into 10 mL of boric acid (H_3BO_3) containing a mixed indicator. After distillation, 0.5 g of Devarda's alloy was added to the same extract to reduce nitrate (NO_3^-) to NH_3, which was distilled under the same conditions and similarly collected. Both distillates were titrated with 0.02 N sulfuric acid (H_2SO_4) until the color changed from green to neutral pink. At the end of the analyses, the distillation unit was rinsed with distilled water. This procedure allowed quantification of ammonium, nitrate, and total mineral N, which are essential indicators of soil fertility. As described in the literature (Sattolo et al., 2016; Liu et al., 2023).

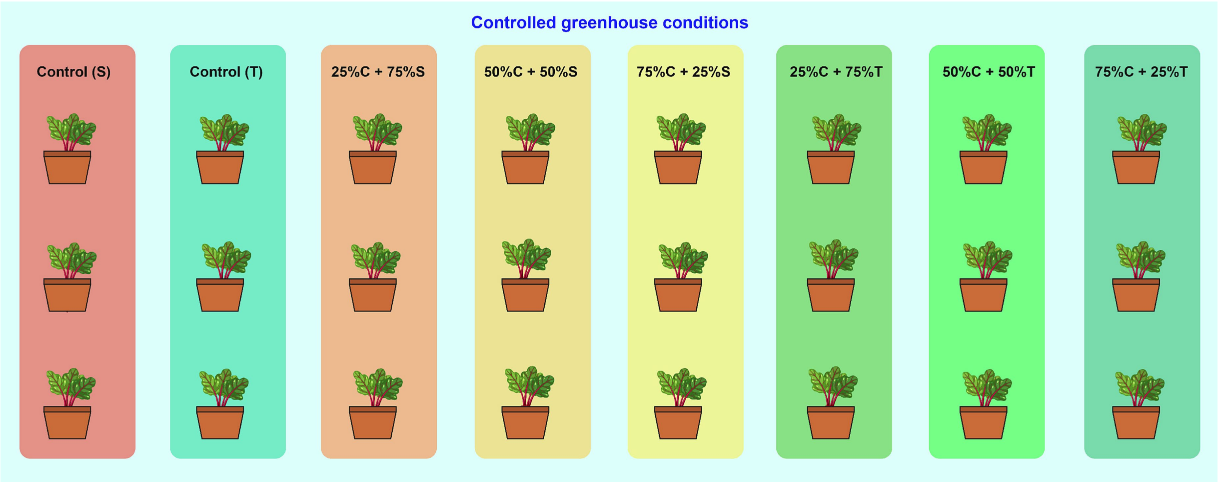


FIGURE 2
Experimental design of the study.

2.5.1.4 Statistical analysis

All statistical analyses were performed in R (version 4.3.2). A one-way analysis of variance (ANOVA) was used to test the effect of substrate treatments on growth and physiological parameters. When significant treatment effects were detected, mean separation was carried out using Tukey's HSD test at $\alpha = 0.05$. Results are presented as means of three replicates ± standard deviation (SD), and different letters within a column indicate statistically significant differences among treatments.

3 Results and discussion

3.1 Evolution of temperature during the composting process

The temperature of compost is a key indicator of microbial activity throughout the composting process, and it is widely used to assess the maturity and stability of the compost (Ahmad and Dar, 2020; Sohal et al., 2021). Monitoring the temperature throughout composting has revealed three distinct phases in the temperature profiles (Figure 3).

The evolution of compost temperature over 150 days (Figure 3) shows the typical three phases of aerobic composting. During the initial mesophilic phase (0–10 days), the temperature increased rapidly from 25 °C to a first peak of 65 °C, reflecting intense microbial activity on easily degradable substrates, as observed similarly in previous findings (Haouas et al., 2021). A slight and rapid decrease (50 °C at day 12) was followed by a second thermophilic peak (68 °C around day 23), corresponding to the degradation of proteins and other labile compounds (carbohydrates, organic acids, and lipids) (Zhou et al., 2014; Haouas et al., 2021). The thermophilic phase persisted for nearly 40 days (days 10–50), maintaining temperatures above 55 °C, which is essential for pathogen inactivation and the effective decomposition of OM (Ahmad and Dar, 2020). After this period, the temperature gradually declined from 55 °C to 35 °C (days 50–100), marking the cooling phase as microbial activity slowed with the depletion of readily available substrates (Haouas et al., 2021). Finally, during the maturation phase (days 100–150), the temperature stabilized at ~25–30 °C, close to ambient, indicating compost stabilization and maturity. This agrees with reports that a thermophilic period of at least 7 consecutive days at a temperature above 50 °C is sufficient to ensure hygienic and mature compost (Yang et al., 2015). Moreover, the temperature profile shown in this graph follows the classical model of the three phases of aerobic composting, as validated by numerous indexed studies. After an initial mesophilic phase, characterized by moderate temperatures (20–40 °C) that sustain the activity of generalist microorganisms, the rapid temperature increase reflects the transition to the thermophilic phase. During this stage, the temperature exceeds 55 °C and approaches 70 °C, remaining at this level for several days. This plateau indicates the intense degradation of readily biodegradable organic matter and the strong activity of specialized microorganisms such as Bacillus and Streptomyces (Liu et al., 2024; Wang et al., 2022). Maintaining temperatures within this thermophilic range is critical for effective compost hygienization, the destruction of pathogens, and the acceleration of organic matter transformation (Policastro and Cesaro, 2022).

The gradual decline in temperature observed from around day 40 corresponds to the maturation phase, during which more complex substrates (lignin, cellulose) are progressively humified by the existing mesophilic microflora (Biyada et al., 2021). This decrease signals the reduction of the easily degradable fraction and the establishment of stable conditions required for microbiologically balanced, stable, and suitable compost maturation (Policastro and Cesaro, 2022). Overall, this thermal profile, consistent with the existing literature, represents a central indicator of an optimal composting process from both

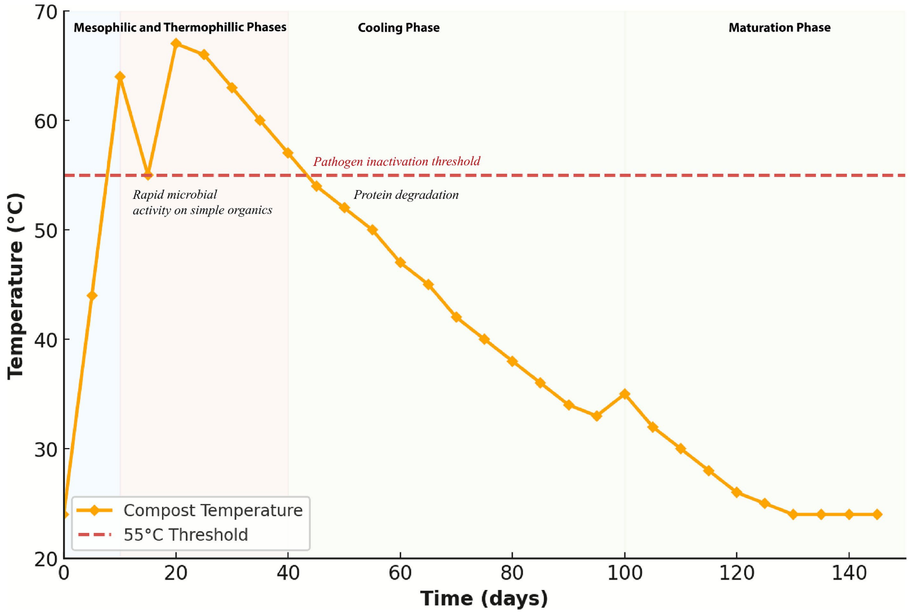


FIGURE 3
Evolution of composting temperature during 150 days.

agronomic and environmental perspectives (Liu et al., 2024; Policastro and Cesaro, 2022; Biyada et al., 2021).

3.2 Physicochemical analyses of the compost amended with sheep manure and commercial fertilizer

The results of physicochemical analysis of the compost before adding sheep manure are presented in the following Table 1.

Table 1 presents the physicochemical characteristics of the compost prior to the addition of sheep manure. On a dry basis, OM content was 62.83%, well above the 30% threshold typically associated with compost stability and soil fertility improvement (Palaniveloo et al., 2020). The TKN remains low (0.68% dry basis), resulting in a high C/N ratio of 46.2. It has been reported that compost maturity best occurs at C/N ratio range of 25–35 (Ho et al., 2022), and some studies cite even 25–40 as optimal (Ucaroglu and Ozbek, 2025). The C/N value significantly exceeds this range, indicating the compost is not yet mature and would benefit from N amendment. A recent meta-analysis recommends maturity criteria including a final C/N $\leq$ 23 and GI $\geq$ 70, with an even more mature compost having GI $\geq$ 90 (Ji et al., 2023), However, our compost reached a high GI, but it cannot be considered mature as the C/N ratio is still high (46.2) in this case study. The pH value of 7.82 falls within the favorable range of 6.0–8.5 for compost stability (Ji et al., 2023), and the low EC (0.51 mS·cm^{-1}) indicates low salinity and minimal phytotoxic risk (Banuelos and Lin, 2008).

TABLE 1 Physicochemical analysis of sheep manure and compost before adding sheep manure.

Parameters	Sheep manure	Compost	
		Raw	Dry
Humidity (%)		51.8	–
Dry matter (%)		48.82	–
TKN (%)	2.00	0.33	0.68
P (%)	0.50	0.07	0.14
K (%)	0.7	0.15	0.30
OM (%)	–	30.67	62.83
TOC (%)	25	15.34	31.42
Mineral matter (%)	–	18.15	37.17
C/N ratio	12.5	46.20	
MgO (%)	–	0.21	0.43
Ca (%)	–	1.70	3.49
Na (mg·kg^{-1})	55.5	0.02	0.05
Cl (%)	–	0.05	0.10
pH	7.5	7.82	–
EC (mS·cm^{-1})	2.5	0.51	–
B mg·kg^{-1}	–	21.22	43.46
Zn (mg·kg^{-1})	–	73.52	150.6
Cu (mg·kg^{-1})	–	7.07	14.49
Mn (mg·kg^{-1})	–	118.7	243.1
Fe (mg·kg^{-1})	–	4,374	8,960

In summary, although the compost exhibits high OM content, a neutral pH, low salinity, and safe levels of heavy metals, its high C/N ratio (46.2) and low TKN (0.68%) indicate incomplete maturity. To produce a mature and agronomically valuable compost, it is recommended to lower the C/N ratio and increase N content by supplementing with a N source such as sheep manure. To improve the quality of our compost, sheep manure was added to our compost in the following proportion: [60% compost + 40% sheep manure (w/w)]. After an additional 30 days of composting, the results illustrated in Table 2 were obtained.

Table 2 summarizes the physicochemical parameters of the compost amended with sheep manure. The compost had a moisture content of 48.19%, corresponding to a dry matter content of 51.81%. Ash content was 45.13%, while OM reached 54.86% and TOC was 27.43%. The N content increased substantially to 1.82%, resulting in a C/N ratio of 15.07. The pH was slightly alkaline at 7.94. Nutrient analysis showed 0.39% of P and 1.70% of K, while EC was 5.6 mS·cm^{-1}, higher than in the non-amended compost. The compost prepared through double maturation and enriched with sheep manure is characterized by an optimal combination of physicochemical parameters, reflecting the efficiency of a fully organic process. Its moderate moisture content (48.19%) supports active microbial life while also ensuring practical manageability during field application (Ji et al., 2023). OM remains at a high level (54.56%), combined with a remarkable TOC (27.43%), which guarantees a stable humus supply, considered an essential factor for long-term soil fertility and structural improvement (Ji et al., 2023). The near-neutral pH (7.94) creates favorable conditions for nutrient availability, promoting beneficial microbial diversity that supports plant growth (Mounirou et al., 2025). A C/N ratio of 15.07 indicates advanced maturity, enabling progressive and balanced N mineralization. The relatively high total N concentration (1.82%) ensures a sustained and consistent nutrient supply for plants, minimizing leaching risks compared to rapid mineral fertilization (Zhang et al., 2022). The P content (0.39 mg·kg^{-1}), although lower than that of chemical fertilizers, originates exclusively from the biomass used and aligns with the principles of sustainable resource valorization, thereby avoiding the risks of soil over-enrichment. K levels (1.7 mg·kg^{-1}) also increased after the addition of sheep manure, but are still low. EC (5.6 mS·cm^{-1}) remains below critical thresholds, confirming this compost's compatibility with most agricultural soils, including its safe use in seedbed preparation. Overall, this 100% organic, agroecological compost provides lasting structural, biological, and agronomic benefits to soils, while supporting environmental preservation and sustainably enhancing farm-level nutrient autonomy. Therefore, while the manure-amended compost showed enhanced maturity and nutrient enrichment, careful management of application rates is necessary to prevent salinity issues. N contained in manure, as in compost, is mostly in organic form, with mineral forms being less present. Plant use of this available N will require mineralization in the soil. Depending on climatic conditions, the N mineralization potential for this type of product is 30 to 40% in the short and medium term. These results confirm the value and benefits of organic waste valorization through the incorporation of sheep manure in producing high-quality compost. Moreover, the final step was to compare the compost amended with sheep manure with a compost amended with commercial fertilizer coming from the

TABLE 2 Physicochemical characteristics of the mature compost after adding sheep manure.

Parameter	Value
Ash (%)	45.13
Humidity (%)	48.19
Dry matter (%)	51.81
TKN (%)	1.82
OM (%)	54.86
TOC (%)	27.43
pH	7.94
P (%)	0.39
K (%)	1.70
EC ($mS\cdot cm^{-1}$)	5.6
C/N ratio	15.07

company Yara Mila HYDROCOMPLEX Partner. The physicochemical characteristics of the compost enriched with these commercial fertilizers are shown in Table 3.

The compost obtained after enrichment with the commercial fertilizer (12-11-18) shows physicochemical characteristics (Table 3) that are strongly influenced by the mineral input. It exhibits a moderate moisture content (29.47%), is suitable for storage and field has application, and a relatively basic pH (7.96), consistent with values reported for most agricultural composts (Mounirou et al., 2025). EC reaches a high level (7.91 $mS\cdot cm^{-1}$), indicating a strong concentration of soluble salts, primarily of artificial origin. NPK formulations often contain Cl salts (such as KCl) as a source of potassium, which explains both the high K and Cl levels. This confirms the high concentration of N present in the Vertisoil (Table 4), likely due to the mismanagement and irrational use of chemical fertilizers used for extensive agricultural production in the region. This condition poses salinity risks to sensitive crops and therefore requires careful management, particularly in low-permeability soils (Zhang et al., 2022). The TOC (12.05%) and the C/N ratio (16.5) suggest apparent maturity; however, this evolution is largely the result of accelerated mineralization induced by the addition of commercial fertilizer, rather than the typical biological processes of organic composting (Ji et al., 2023). TKN (0.73%) and the levels of $N–NH_4$ (357.3 $mg\cdot kg^{-1}$), P_2O_5 (17.66 $mg\cdot kg^{-1}$), and K_2O (3,250 $mg\cdot kg^{-1}$) derive primarily from the mineral fertilizer rather than the natural valorization of biomass. While this composition provides a rapid fertilizing effect, it does not ensure the formation of stable humus nor the enrichment of soil microbial activity, both of which are essential components of long-term compost quality (Zhang et al., 2022). Furthermore, this mode of enrichment exposes soils to potential nutrient losses through leaching and to possible long-term imbalances in soil microbiology (Mounirou et al., 2025).

Consequently, although this compost temporarily meets the analytical criteria required for agricultural amendments, it lacks the structural, microbial, and ecological benefits of a fully organic compost. These aspects will be further examined in the subsequent sections of this study. The analysis of Table 3 highlights the contrasting nature of commercial mineral fertilizers and organic composts. The NPK fertilizer is highly concentrated, providing immediately available macronutrients that ensure rapid plant uptake and yield response. However, its low OM and extremely low C/N ratio mean it contributes little to soil structure, microbial activity, or long-term carbon sequestration.

TABLE 3 Physicochemical analysis of the compost amended with commercial fertilizer.

Parameters	Result
Moisture ($g\cdot100^{-1}$ g)	29.47
Dry matter ($g\cdot100^{-1}$ g)	70.53
pH	7.96
EC ($mS\cdot cm^{-1}$)	7.91
OM ($g\cdot100^{-1}$ g)	24.09
TOC ($g\cdot100^{-1}$ g)	12.05
Cl (%)	0.38
$N–NH_4$ ($mg\cdot kg^{-1}$)	357.3
$N–NO_3$ ($mg\cdot kg^{-1}$)	236.9
TKN ($g\cdot100^{-1}$ g)	0.73
C/N ratio	16.50
P_2O_5 ($mg\cdot kg^{-1}$)	17.66
K_2O (%)	0.33
Na ($mg\cdot kg^{-1}$)	587.5
MgO (%)	0.03
CaO (%)	0.06
Cu ($mg\cdot kg^{-1}$)	0.22
Mn ($mg\cdot kg^{-1}$)	0.14
Fe ($mg\cdot kg^{-1}$)	3.78

TABLE 4 Physicochemical parameters of soils used in this study.

Parameters	Fluvisol soil	Vertisol soil
pH	7.93	7.56
EC ($dS\cdot m^{-1}$)	0.08	0.39
Total limestone (%)	2.15	21.30
SOM (%)	0.48	2.72
TOC (%)	0.28	1.58
Ammoniacal N (ppm)	32.40	51.48
Nitric N (ppm)	97.96	500.96
Mineral N (ppm)	130.4	552.4
Available P (ppm)	50.6	66.2
Exchangeable K (ppm)	53	252

In contrast, compost with sheep manure (Table 2) supplies lower concentrations of nutrients but provides substantial OM, a balanced C/N ratio, improved soil quality, and is considered sustainable for long-term application. This organic amendment plays a key role in improving soil aggregation, water retention, microbial diversity, and nutrient cycling. Its higher EC, however, suggests careful management of application rates to avoid salinity risks. Recent studies support the combination of organic and inorganic fertilizers as the most effective strategy. For example, Bo et al. (2025) found that partial substitution of chemical fertilizers with compost improved wheat productivity and soil quality, without introducing risks associated with heavy metals. Similarly, Diatta et al. (2024) demonstrated that combining compost with inorganic fertilizers can reduce synthetic fertilizer use by approximately 50% while maintaining the same production. Gil-Martínez et al. (2025) showed that organic amendments significantly enhance soil organic carbon and microbial activity, contributing to long-term soil resilience. Overall, while NPK is essential for immediate nutrient supply, compost ensures long-term sustainability. An integrated fertilization strategy that combines both is widely recommended to achieve high crop productivity, enhance soil fertility, and support sustainable agricultural practices.

3.2.1 Soil analysis

The results of Table 4 showed that both soils were slightly alkaline, with pH values of 7.93 for the Fluvisol soil and 7.56 for the Vertisol soil. EC remained low in both cases (0.08 and 0.39 dS m^{-1}, respectively), indicating a low salinity level for crop growth. However, the two soils differed considerably in their limestone content, with the Vertisol soil being highly calcareous (21.3%) compared to the Fluvisol soil (2.15%), a factor that can significantly reduce the availability of P and micronutrients (Halajnia et al., 2009).

In terms of SOM, the Fluvisol soil was poor (0.48%) as expected, reflecting a low capacity for water and nutrient retention, whereas the Vertisol soil is considered rich and fertile (2.72%). A similar trend was observed for TOC (0.28% for Fluvisol soil and 1.58% for Vertisol soil). The N status also showed a significant contrast, with total mineral N at 130 ppm in Fluvisol soil compared to 552 ppm in Vertisol soil. Notably, the latter was particularly rich in nitric-N (500 ppm), indicating the presence of a suitable N form available for crop uptake. In our case, high N levels are common after over-fertilization or the application of manure. Still, they are generally not sustainable, because much of that N is subjected to leaching or denitrification losses (Cameron et al., 2013). P levels were satisfactory in both soils (50.6 ppm in Fluvisol soil and 66.2 ppm in Vertisol soil). Nevertheless, the high calcareous nature of the Vertisol soil may lead to P fixation, limiting its actual availability to plants. Exchangeable K is essential for plant nutrition, stress tolerance, and yield quality. Low levels in Fluvisol soil (53 ppm) reflect poor nutrient retention and a higher leaching risk, while higher levels in Vertisol (252 ppm) indicate a greater fertility potential and stronger nutrient buffering capacity.

Overall, the Fluvisol soil is characterized by low SOM and limited fertility, requiring regular applications of organic amendments such as manure or compost to improve its characteristics. The Vertisol soil, despite being highly calcareous, is much more fertile due to its higher SOM, N, P and K contents. However, the excess limestone remains a constraint to nutrient availability, and this limitation could be mitigated through increased P fertilization and foliar applications of micronutrients.

3.3 Agronomic test and physiological response of beetroot to the different treatments

To evaluate the agronomic and physiological impact of compost-soil mixtures, beetroot (*Beta vulgaris* var. *Plat d'Égypte*) was grown under controlled greenhouse conditions using different proportions of compost with Fluvisol and Vertisol soils as described above. Plant growth (roots, stems and leaves) and physiological parameters (chlorophyll index and chlorophyll fluorescence, Fv/Fm) were measured to assess the influence of compost on biomass accumulation and photosynthetic performance. The results are illustrated in Figure 4 as follows.

It should be mentioned that the fruit in this manuscript refers to the edible part of beetroot. Compost addition significantly enhanced the biomass of both the edible fruits and roots (a, b) compared to controls. The 25%C + 75%S treatment produced the largest fruit biomass (group a), while the lowest yields were consistently recorded in the control groups. For root biomass, a similar peak was observed in the 25%C + 75%S mixture. These increases are attributed to improved soil water-holding capacity and nutrient retention in the sandy Fluvisol, and a reduction in P fixation in the calcareous Vertisol. Interestingly, higher compost rates (75%) did not consistently produce the highest yields, suggesting a practical optimum at 25% compost for biomass accumulation.

Biomass production for stems and leaves (c) followed a positive trend, with all compost treatments performing significantly better than the controls, although they did not show significant differences between the various compost concentrations themselves. This broader canopy development supports the production of assimilates necessary for both root and fruit growth. The Chlorophyll Index (d) increased markedly with compost addition, reaching its maximum in the 75%C + 25%T treatment. These higher CI values reflect greater N and P availability, which are essential for chlorophyll biosynthesis. In contrast, the lowest index values were observed in the unamended Control S. Moreover, Chlorophyll fluorescence measurements indicated generally healthy photosynthetic performance across most treatments. While absolute values were slightly lower than the typical range for unstressed plants (0.79–0.83), the results showed relative improvements in PSII photochemistry under compost addition. The 25%C + 75%S and 75%C + 25%S treatments maintained similar performance to the controls and other treatments, with only a minor reduction noted in the 50%C + 50%S treatment.

The advantages of compost addition are consistent with known soil and plant processes, and generally, the trends in our results fit together with the existing literature. In Fluvisol soils, compost improves water-holding capacity and nutrient retention, which enhances biomass accumulation compared to unamended soils, as highlighted in the literature (Posmanik et al., 2023). In calcareous matrices such as Vertisol, compost can reduce P fixation and improve the availability of micronutrients like Fe and Zn, mitigating the nutrient limitations imposed by $CaCO_3$-rich soils (Zhang et al., 2022; Baccari and Krouma, 2023; Nsiri and Krouma, 2023). These mechanisms explain why the composted Vertisol mixtures, particularly 25%C + 75%T in our findings, performed better in terms of root and shoot biomass. The significant increases in CI observed in compost treatments can reflect greater N and P availability, which directly support chlorophyll biosynthesis and photosynthetic capacity, as reported by different authors (Suvendran et al., 2023; Lucchetta et al., 2023). These findings align with previous studies that have shown compost improves beetroot growth and yield by enhancing nutrient supply and water retention, while simultaneously alleviating abiotic stress by positively

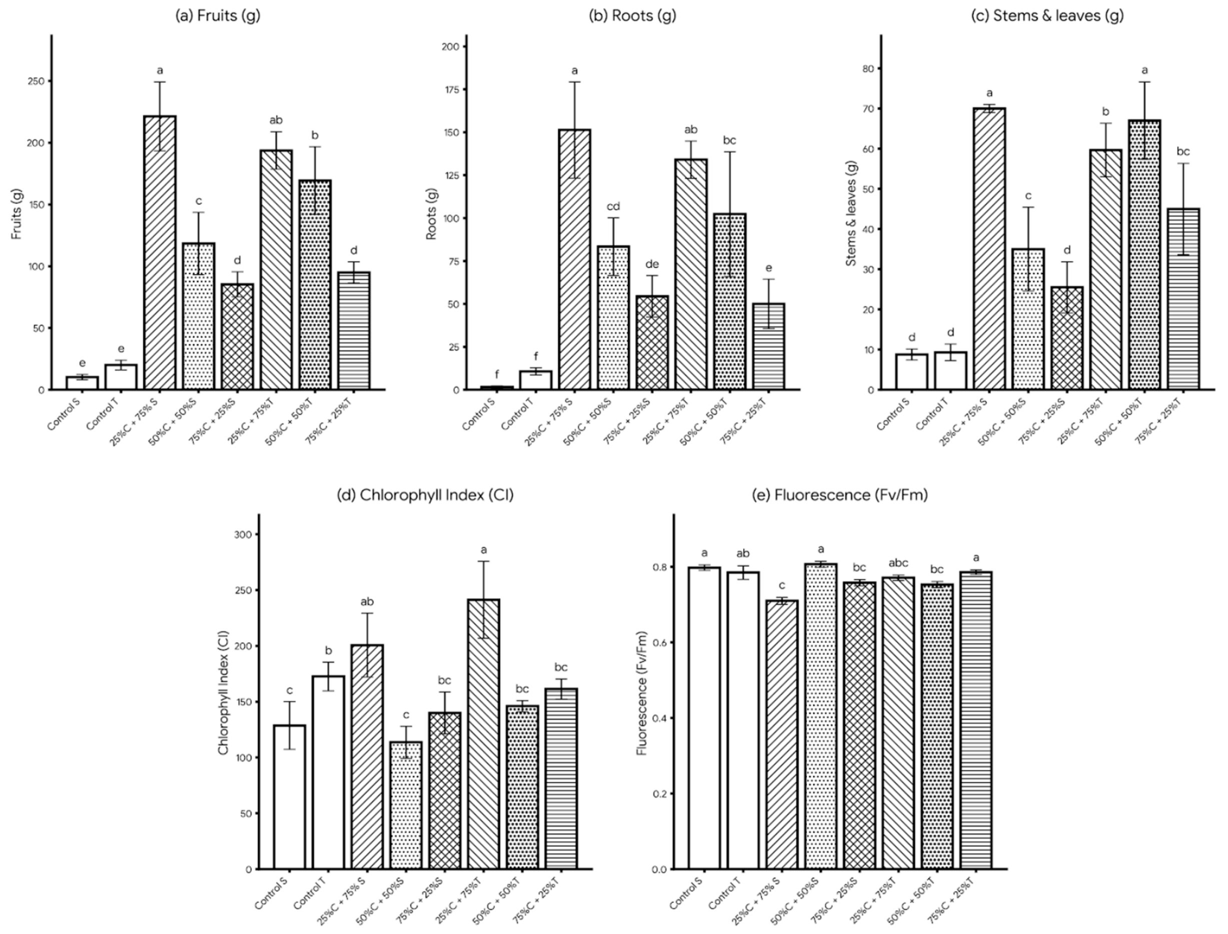


FIGURE 4
Growth and physiological responses of beetroot (*Beta vulgaris* var. Plat d'Égypte) under different compost–soil mixtures in greenhouse conditions. Bars represent mean values (±SD, *n* = 3). Different letters above bars indicate significant differences among treatments according to one-way ANOVA followed by Tukey's HSD test ($p < 0.05$). **(a)** Fruits (g); **(b)** Roots (g); **(c)** Stems & leaves (g); **(d)** Chlorophyll index (CI); **(e)** Fluorescence (Fv/Fm).

impacting the behavior and mechanisms of nutrients within the water, soil, and plant system (Abd El-Mageed et al., 2019). In addition, the observed increases in Fv/Fm values showed no significant differences among treatments, although lower in absolute value than the typical range for dark-adapted leaves (0.79–0.83), still indicate relative improvements in PSII performance under compost addition, consistent with literature showing higher fluorescence values in non-stressed plants compared to controls (Bartold et al., 2024; Kalaji et al., 2012). Overall, the results highlight that even modest compost additions (e.g., 25%C + 75%S) substantially improve both agronomic and physiological performance of beetroot in contrasting soils. This suggests that compost amendments represent a practical strategy to enhance productivity and mitigate nutrient limitations in Fluvisol and calcareous soils.

Moreover, the number of leaves at the harvesting stage (Figure 5) followed a similar trend to the other growth traits, with compost-amended treatments producing more foliage than the controls. Both controls (S and T) yielded the fewest leaves (6 per plant). The highest values were observed in the 25%C + 75%S (12 leaves) and 25%C + 75%T (11 leaves) treatments, while intermediate results were found in 50%C + 50%S, 75%C + 25%S, 50%C + 50%T and 75%C + 25%T (8–9 leaves).

The greater number of leaves in the 25% compost mixtures is consistent with the higher biomass production (fruits, roots, stems and leaves) and improved physiological status (chlorophyll index and Fv/Fm) observed in the same treatments. Leaf number is a critical determinant of canopy development and photosynthetic surface area, which directly supports assimilate production for root and fruit growth (Fallah et al., 2025). The limited leaf formation in unamended controls reflects poor nutrient availability in the Fluvisol soil and strong P and micronutrient fixation in the calcareous Vertisol soil, both of which restrict vegetative growth (Zhang et al., 2022; Krouma, 2023). Taken together, these results show that compost addition not only enhanced below-ground traits (root diameter, biomass) and above-ground parameters (stems, shoots), but also promoted greater canopy development, as seen in the increased number of leaves. This effect was most pronounced when compost was combined with 75% of soil (Fluvisol or Vertisol), highlighting that low to moderate compost rates (25%) are sufficient to maximize both vegetative growth and physiological efficiency. This synergistic improvement across all traits confirms the central role of organic amendments in overcoming the nutrient and structural limitations of both Fluvisol and calcareous soils (Posmanik et al., 2023; Abd El-Mageed et al., 2019).

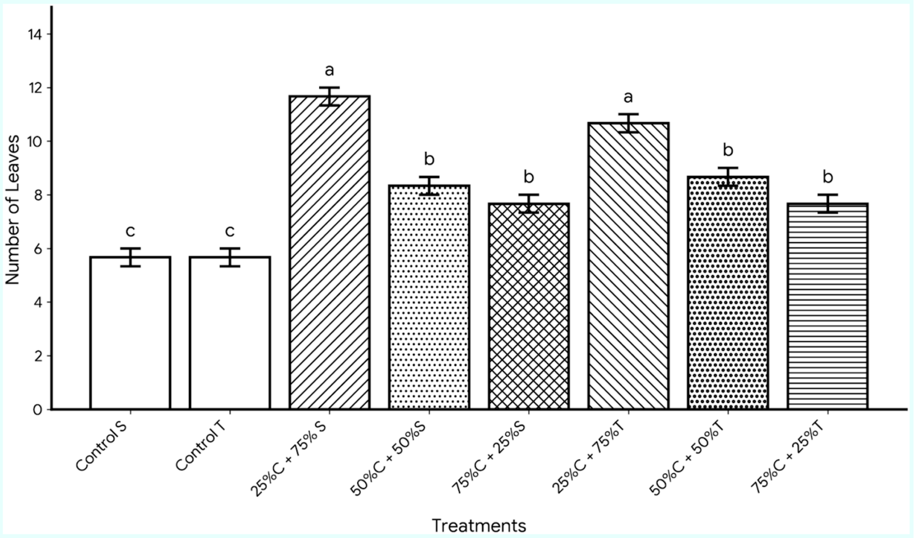


FIGURE 5
Number of leaves for each treatment at the harvesting stage.

4 Conclusion

This study demonstrates that the integration of sheep manure into an industrial compost formulated from hydrodistillation residues and strawberry waste substantially improves the agronomic quality of the final product. The increase in total nitrogen to 1.82% and the reduction of the C/N ratio to 15.07 confirm the maturity and stability of the compost, while maintaining high levels of OM and TOC that support soil fertility. The slightly alkaline pH (~7.9) remains compatible with a wide range of crops, though the high EC requires careful management of application rates according to crop sensitivity and soil conditions. The experiment confirmed the agronomic value of this compost at moderate doses (25%). In Fluvisol soil, the addition of compost increased biomass (fruits, roots, stems/leaves) by enhancing water retention and nutrient availability. In calcareous Vertisol soils, the compost reduced P fixation and improved micronutrient availability, resulting in higher CI values and enhanced fluorescence (Fv/Fm). The trends of responses (biomass, CI, Fv/Fm, leaf number) indicate a coherent improvement in soil–plant interaction, with a practical optimum observed at 25% compost for both soils. From an operational perspective, three recommendations emerge. First, moderate application rates (25% v/v in substrate or adjusted doses based on EC and crop tolerance) should be prioritized to balance nutrient availability and salinity risks. Second, application strategies should be adapted to soil type: in Fluvisol soils, target improvements in water retention and reduced leaching losses; in calcareous soils, combine compost with balanced P management and, if necessary, foliar micronutrient supplementation. Third, integrate this compost into combined fertilization strategies (organic + mineral) to secure both short-term yield responses and long-term soil functions (structure, microbial activity, carbon storage). This work contributes to addressing the current lack of agronomic validation for compost derived from Moroccan industrial by-products by providing experimental evidence of maturity, fertilizing value and efficiency under controlled conditions. In summary, the addition of sheep manure to locally available industrial compost produces a mature, nutrient-rich, and agronomically effective organic amendment, particularly suited to moderate application rates. When combined with integrated fertilization, this resource can sustainably increase crop productivity (e.g., beet), enhance the quality of both Fluvisol and calcareous soils, and support the development of territorial biowaste valorization chains consistent with agroecological and climate objectives. This strategy provides an immediate, scalable, and policy-aligned lever to accelerate the transition toward more resilient, low-input agroecosystems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SB: Resources, Writing – original draft, Formal analysis, Conceptualization, Writing – review & editing, Investigation. YM: Writing – review & editing. AT: Formal analysis, Writing – review & editing, Data curation, Writing – original draft. FE: Writing – review & editing, Validation, Formal analysis. RH: Writing – review & editing. ML: Writing – review & editing. MO: Resources, Conceptualization, Supervision, Writing – review & editing, Validation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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