

Article

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

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Abstract: Organic waste utilization stands as a pivotal approach to ecological and economic sustainability. This study aimed to assess the stability, maturity, and evolution of co-composts comprising various blends of green waste (GW) and sheep manure (SM). Employing a diverse array of physico-chemical and biological parameters, we investigated the co-composting process over 120 days. Three types of garden waste (mixture of green waste (MGW), fallen leaves (FL), and grass cutting (GC)) were utilized. The results revealed significant compost transformation, evident by odor and insect absence and a shift to dark brown coloration, indicating maturation. The compost C2, derived from FL, exhibited superior soil amendment potential. Significantly, it exhibited a pH level of 6.80, an EC of 2.45 mS/cm, and an OM content of 55%, along with a C/N ratio of 16.15. Analysis of the macronutrients revealed values of 1.98% for TN, 3.22% for TP, and 0.61% for K. Crucially, the compost showed no phytotoxic effects and boasted a high GI of 94.20% and a low respiration rate of 4.02 mg/50 g, indicating its stability and appropriateness for agricultural application. Our findings underscore compost's potential as an eco-friendly soil amendment, offering valuable insights for sustainable agricultural management and supporting the circular economy.

Keywords: circular economy; co-composting; green waste; maturity; phytotoxicity; physico-chemical properties; sheep manure; stability

1. Introduction

The surge in urban green space expansion worldwide has contributed to a notable uptick in the generation of garden waste. With more engagement in the maintenance of green spaces, the volume of organic waste (OW) generated has increased. Consequently, the accumulation of these wastes poses challenges for municipal waste management systems and can lead to environmental degradation if not properly addressed. This phenomenon has emerged as a pressing environmental issue in both developing and developed nations [1]. The environmental ramifications of this trend are increasingly apparent, necessitating concerted efforts for sustainable waste management practices.

Nowadays, the valorization of OW stands as a crucial strategy in safeguarding both human and environmental health. Within this context, composting emerges as a recognized method, offering an effective, ecological, economical, and sustainable approach to recycle

OW [2]. Composting stands out as the predominant and widely adopted approach for managing OW [3,4]. Researchers universally agree that composting entails the transformation and stabilization of organic material into a resilient humus-like substance resembling natural soil humic compounds [5,6]. Recognized for its efficiency, composting emerges as a leading technology for OW treatment and disposal, effectively curbing environmental pollution while yielding compost suitable for fertilizer and soil improvement, devoid of phytotoxicity and pathogens [7]. This natural biological process involves the intricate decay of organic matter (OM) through biochemical decomposition, facilitated by the collaborative action of fungi, bacteria, and other microorganisms within a conducive growth environment, yielding a stable and nutrient-rich material ideal for organic fertilizer applications [4,8,9]. The composting end-product improves soil properties, promotes plant growth, sequesters carbon, increases water-holding capacity, helps in the elimination of pests and weeds, and offers an alternative to synthetic fertilizers [9–11]. The circular economy concept is further supported through the composting of green waste (GW), which reduces garden waste volume and recycles nutrients into fertilizers, mitigating municipal solid waste accumulation [1]. Moreover, composting proves to be an efficient and economical method for treating animal manure (AM) before land application and promoting recycling efforts [10]. Co-composting, as suggested by [5], involving multiple organic materials, is anticipated to address the limitations of composting individual materials. Moreover, incorporating AM into GW composting has been shown to enhance humification processes [12], while the addition of feces to composting mixtures rich in lignocellulosic residues accelerates the degradation of cellulose and hemicellulose molecules [13]. The AM undergoes a transformative shift when subjected to aerobic fermentation processes and attains specified quality benchmarks, ceasing to be categorized as mere waste. This perspective resonates with waste hierarchy strategies, emphasizing reduction, reuse, recycling, recovery, and disposal as sequential approaches to minimize resource consumption and promote sustainable recycling practices [14,15].

Enhancing our comprehension of compost properties proves pivotal for advancing our understanding of decomposition processes and refining composting techniques [9]. The literature underscores the significance of several key parameters commonly employed to manage and regulate composting progress, ensuring the attainment of high-quality end-products [3]. Research reveals that the composting process and the resultant product quality are multifactorial, contingent upon characteristics such as the nature of the raw materials, moisture levels, frequency of turning, microbial activity, and environmental conditions, particularly evident in open pile systems [2,5]. The quality of compost is intricately linked to its maturity and stability, which can be evaluated through diverse physico-chemical and biological parameters utilizing advanced detection technologies [2]. However, the challenge lies in controlling and optimizing the intricate and dynamic interactions among biological, chemical, and physical mechanisms within heterogeneous organic matrices [3]. These parameters are assigned score values and weighting factors based on scientific insights into their roles in enhancing soil productivity [16]. Despite the wealth of information available, there remains a lack of consensus regarding the most suitable method for assessing the stability and maturity of quality parameters [17]. The terms stability and maturity are frequently employed, though often with nuanced distinctions. Broadly, stability and maturity serve as crucial criteria for determining the culmination of decomposition processes and signify the readiness of compost for specific applications. Stability denotes the extent of OM breakdown achieved through microbial activity, coupled with resistance to further decomposition. Conversely, maturity pertains to the decomposition of OM and the neutralization of phytotoxic substances, indicating compost readiness for designated end uses [18].

The objective of this study is to evaluate the stability, maturity, and evolution of composts produced from various combination GW and SM. The specific aims of this research are as follows: (1) to characterize and assess the physico-chemical and biological properties of the composts that determine their suitability for agricultural applications;

(2) to employ multivariate statistical analyses, including PCA and Pearson's correlation, to elucidate the different characteristics of the composts; and (3) to provide practical recommendations for the application of mature composts.

2. Materials and Methods

2.1. Study Area

The research was conducted at the National Institute of Agricultural Research (INRA) in Rabat, Morocco, utilizing an established composting facility situated within the Botanic Garden site, centrally located in Rabat. The city, positioned at 34°00'47" N latitude and 6°49'57" W longitude, maintains an elevation of 46 m. Rabat experiences a temperate Mediterranean climate, characterized by average ambient temperatures ranging from 16.6 °C (61.8 °F) to 26.6 °C (71 °F). This geographical and climatic setting provides an ideal environment for conducting composting experiments, ensuring consistent conditions conducive to the study of composting processes and their outcomes.

2.2. Raw Material

The experimental setup involved the utilization of three distinct types of GW obtained from the Botanic Garden of INRA in Rabat, Morocco, namely MGW, FL, and GC. To ensure safety and efficacy, diseased plants were excluded from the study due to their potential toxicity. The SM, sourced from the INRA sheep farm in El Koudia, was meticulously collected and transported to the composting site immediately following pen cleaning activities. Additionally, durum wheat straw (WS) served as a bulking agent in the composting process. Prior to composting, the GW underwent thorough cleaning to remove unwanted materials such as wrapping papers, plastics, cans, and sticks, following which it was homogenized via shredding to achieve a diameter of 4–10 cm using a leafcutter. The physico-chemical characteristics of all the raw materials utilized in the experiment are detailed in Table 1.

Table 1. Initial physico-chemical parameters of feedstock materials.

Parameters	Units	MGW	FL	GC	WS	SM
TOC	%DM	14.18	42.77	20.11	35.12	29.45
OM	%DM	24	78.98	35.40	60.40	53.36
Ash	%DM	76	21.02	64.60	39.60	46.64
TN	%DM	0.40	1.12	0.60	0.95	1.01
pH	-	7.16	7.05	7.10	6.5	8.05
EC	mS/cm	3.09	3.95	4.87	0.6	4.66

2.3. Experimental Setup and Sampling

All composts were meticulously prepared utilizing an aerated static windrow technique, each in a controlled environment. The experiment took place in a defined composting place, with dimensions of 40 m in length, 2 m in width, and 1.2 m in height, facilitating optimal composting conditions. Additionally, trapezoidal windrow composting experiments were conducted, featuring dimensions of 2.5 m in length, 2 m in width, and 1 m in height. The composition of the raw materials, detailed in Table 2, aimed to achieve theoretical carbon-to-nitrogen (C/N) ratios ranging between 30 and 40. The total weight of raw materials in each windrow was approximately 2 tons.

Table 2. Co-compost mixture content.

Treatment	Mixture Content
C1	30% SM + 10% WS + 60% MGW
C2	30% SM + 10% WS + 60% FL
C3	30% SM + 10% WS + 60% GC

Temperature measurements were taken every three days at nine points and various depths (20 cm, 50 cm, and 70 cm from the top of the pile) throughout the 120-day composting period, beginning from October 2023 to March 2024, with sampling intervals of 15 days. Employing a multi-point sampling approach, fresh compost samples (500 g each) were collected from three distinct locations within the piles (surface, bottom, and corners), sealed in air-tight polythene bags, and labeled for subsequent analysis. Manual turning of the compost piles occurred regularly, ensuring thorough mixing to maintain porosity and promote homogeneity. During the most active phase, windrows were turned weekly, followed by monthly turns for the remainder of the composting duration. To prevent excessive heat loss, composting mounds were covered with polythene sheets. The initial moisture content of composting piles was adjusted and maintained at approximately 60% [19]. All samples were promptly transferred to the laboratory and stored at 4 °C for subsequent physico-chemical analysis and seed germination tests. The flow-sheet of our study is represented in Figure 1.

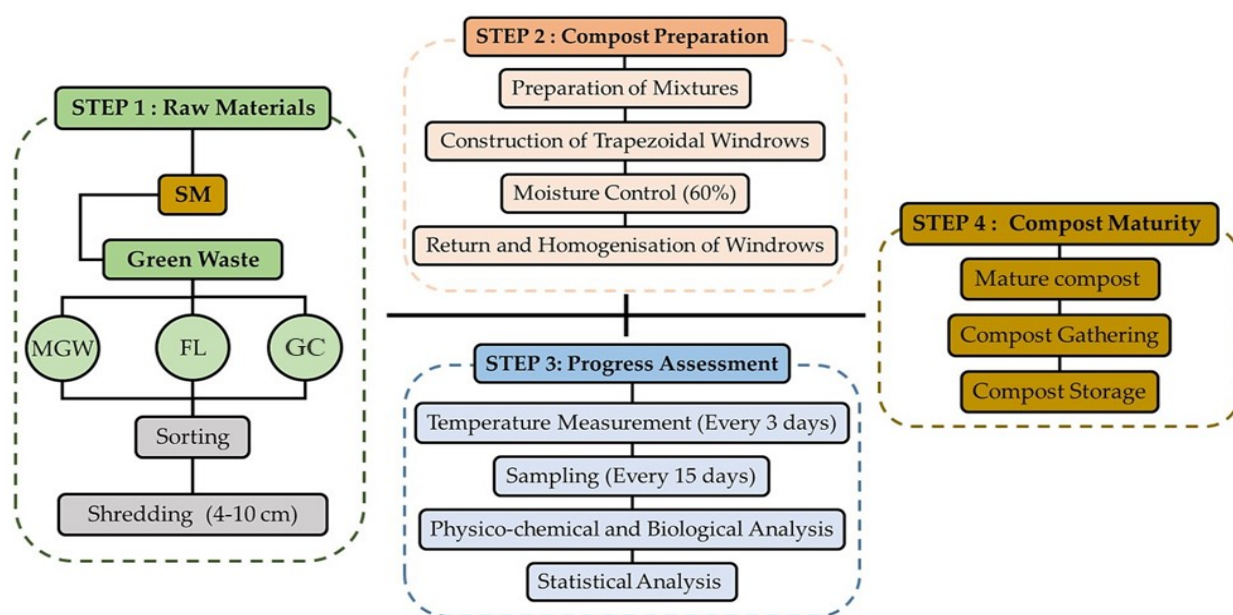


Figure 1. The flow-sheet of the co-compost processing.

2.4. Physico-Chemical Parameters

Following the completion of the 120-day composting period, 500 g of each compost preparation underwent drying in oven at 60 °C for a duration of 12 h. Subsequently, the dried samples were finely ground to achieve a homogeneous consistency and sieved to obtain particles with a diameter of 0.2 mm. These processed samples were then subjected to physico-chemical analyses employing standardized methods. To ensure accuracy and reliability, all measurements were conducted in triplicate ($n = 3$). The temperature of the windrow was monitored utilizing a compost thermometer (−20–110 °C), with readings taken at 9 different points and subsequently averaged. pH and electrical conductivity (EC) were determined using a mixture of material and deionized water prepared at a ratio of 1:5 (w/v), and subsequent suspensions were subjected to analysis using a digital pH-meter (Mettler Toledo Seven Easy-728 Metrohm) and a conductivity meter (ORION, model 162) [20,21]. The dry matter (DM) of the samples were assessed by subjecting them to drying until reaching a constant weight at 105 °C in a hot air oven over a period of 12 h [22]. The volatile solids (VS), along with OM, were evaluated through DM determination and weight loss upon ignition at 550 °C for 4 h using a muffle furnace [2,23]. The determination of total organic carbon (TOC) was carried out by dividing the OM content by a factor of 1.72 [9]. The ash content was assessed using the loss-on-ignition method [24]. The Kjeldahl total nitrogen (TN) was determined using the Kjeldahl method [25]. The

phosphorus content (TP) in the compost samples was analyzed through colorimetry at 882 nm utilizing a spectrophotometer (JENWAY 6405), following the Olsen method [11]. The UV absorbance of the humic acid (HA) extracted from the sample underwent measurement using a spectrophotometer, with readings taken at wavelengths of 465 nm and 665 nm [26]. The ratio of the absorbance values at these two wavelengths denoted as E_4/E_6 , was calculated, serving as an important parameter indicative of the degree of humification. The concentrations of ammonium ($N-NH_4$) and nitrate ($N-NO_3$) were analyzed using ion chromatography applied to a 1:20 (w/v) water extract [22]. For the assessment of mineral nutrient concentrations, the calcined DM of each sample was subjected to solubilization in concentrated hydrochloric acid (HCL), followed by filtration through Whatman number 42 μm filter paper and subsequent dilution to a volume of 100 mL with distilled water [27]. Subsequently, the concentrations of iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), magnesium (Mg), and calcium (Ca) in the resulting filtrate were determined using atomic absorption spectrophotometry (AAS). Furthermore, the concentrations of potassium (K) and sodium (Na) in the filtrate of each compost sample were assessed using a flame photometer (model CL 378) [11].

2.5. Biological Analysis

To determine the germination index (GI), 5 g of dry-weight compost sample was mixed with 50 mL of distilled water and agitated on a shaker for 24 h [28]. Following extraction, 5 mL of the filtrate was dispensed into a 9 cm-diameter petri dish, containing two pieces of sterilized Whatman filter paper and 10 garden seeds (*Lepidium sativum*). Distilled water served as the control. Each petri dish was then placed in darkness at a temperature of 25 ± 5 °C for 72 h. This process was replicated three times to ensure consistency. After incubation, the number of germinated seeds was recorded, and the length of each seed root was measured. The GI was calculated using Equation (1):

$$GI\% = \frac{\text{Mean of germinated seed in the sample} \times \text{Mean of root length in the sample}}{\text{Mean of germinated seeds in the control} \times \text{Mean of root length in the control}} \times 100 \quad (1)$$

Garden seeds were chosen for their rapid germination and sensitivity to phytotoxic compounds, making them suitable indicators for assessing compost quality and potential phytotoxicity effects.

Microbial respiration was assessed following the modified protocol of [2]. In this method, compost samples (50 g each) were adjusted to a humidity level of 60% and subsequently incubated for 24 h in 1 L bottles, each containing a tube filled with 10 mL of 0.1 N sodium hydroxide. During incubation, microorganisms present in the compost consumed oxygen (O_2) and produced carbon dioxide (CO_2), which was absorbed by the sodium hydroxide solution. Following incubation, the amount of absorbed CO_2 was determined through titration with 0.1 N HCl using phenolphthalein as a pH indicator. The quantity of absorbed CO_2 was then calculated using Equation (2):

$$C-CO_2(\text{mg}/50 \text{ g of compost}) = (\text{Control } V(\text{HCl}) - \text{Sample } V(\text{HCl})) \times 2 \quad (2)$$

2.6. Statistical Analysis

The data were submitted to variance analysis using IBM SPSS Statistics 25. Principal component analysis (PCA) was used to examine the multivariate relationship between the physico-chemical and biological parameters' progress during the co-composting. Pearson's correlation coefficient (r) was used to evaluate the linear correlation between two parameters ($p < 0.05$) [29].

3. Results and Discussion

3.1. Temperature Profile

The temporal evolution of temperature in various co-compost piles is illustrated in (Figure 2).

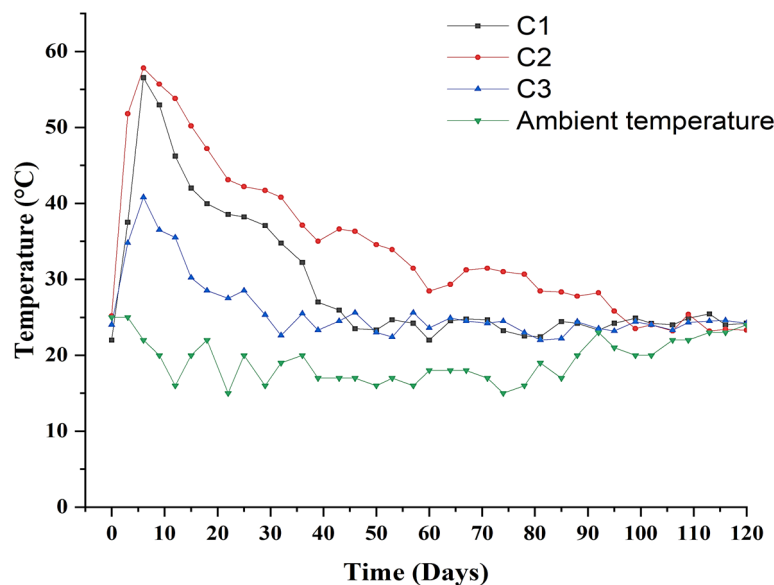


Figure 2. Temperature evolution in various co-compost piles over time.

The ambient temperature ranged between 20 °C and 25 °C. During the initial 5 days, a swift elevation in pile temperatures occurred, indicative of abundant degradable compounds. Notably, on the sixth day, C2 exhibited the highest temperature of 57.8 °C, succeeded by C1 at 56.6 °C, while C3 reached 40.8 °C. Subsequently, C1 and C2 sustained temperatures above 55 °C for 6 and 3 days, respectively, whereas C3 did not surpass 41 °C. Wang et al. (2017) [30] indicated that a 3-day thermophilic phase suffices for most composts to achieve weed seed and pathogen sanitation requirements, cautioning against prolonged high temperatures due to potential adverse chemical alterations in OM and microbial activity retardation. Moreover, [31] stated that temperatures exceeding 45 °C are adequate for pathogen reduction in compost heaps. Significant temperature disparities were observed between C1, C2, and C3. It is hypothesized that the shorter duration of sunlight exposure (less than 5 h) for C3, compared to more than 7 h for the other piles, potentially impeded biodegradation processes. Further investigation into the influence of sunlight exposure on uncovered composting units is warranted. Beyond 20 days, the temperatures across all treatments exhibited a declining trend, with C1 and C2 reaching the maturation phase (<30 °C) on Days 39 and 29 respectively, signifying the stabilization of organic compounds and microbial activity reduction; thus, the temperature gradually decreased and remained mostly within the ambient temperature marking the end of the process. In the initial stages of the co-composting process, the raw material exhibited a light brown hue and possessed a large particle size, accompanied with a malodorous scent. After 120 days, the compost underwent a significant transformation characterized by the absence of odors, insects, and with a transition to a dark brown coloration, indicative of maturation.

3.2. EC and pH Progress

The pH serves as a crucial determinant in the composting process. The optimal pH range for high-quality compost production falls between 6.5 and 7.5 [32]. pH is an important factor governing nitrogen (N) losses through ammonia volatilization, particularly accentuated at pH levels exceeding 7.5 [33]. As depicted in (Figure 3a), the initial pH values in C1, C2, and C3 were recorded at 7.42, 7.10, and 7.10, respectively, subsequently declining to 6.61, 6.80, and 5.90 by the end of the process.

These discernible pH variations are attributed to the presence of hydrogen ions throughout composting, which influence microbial community activity [1]. At the end of the process, pH stabilizes alongside the biosynthesis of humic substances [34–36]. According to [37,38], the final pH values of C1 and C2 fall within the recommended compost standard range of 6.0 to 7.5, affirming their suitability for soil amendment.

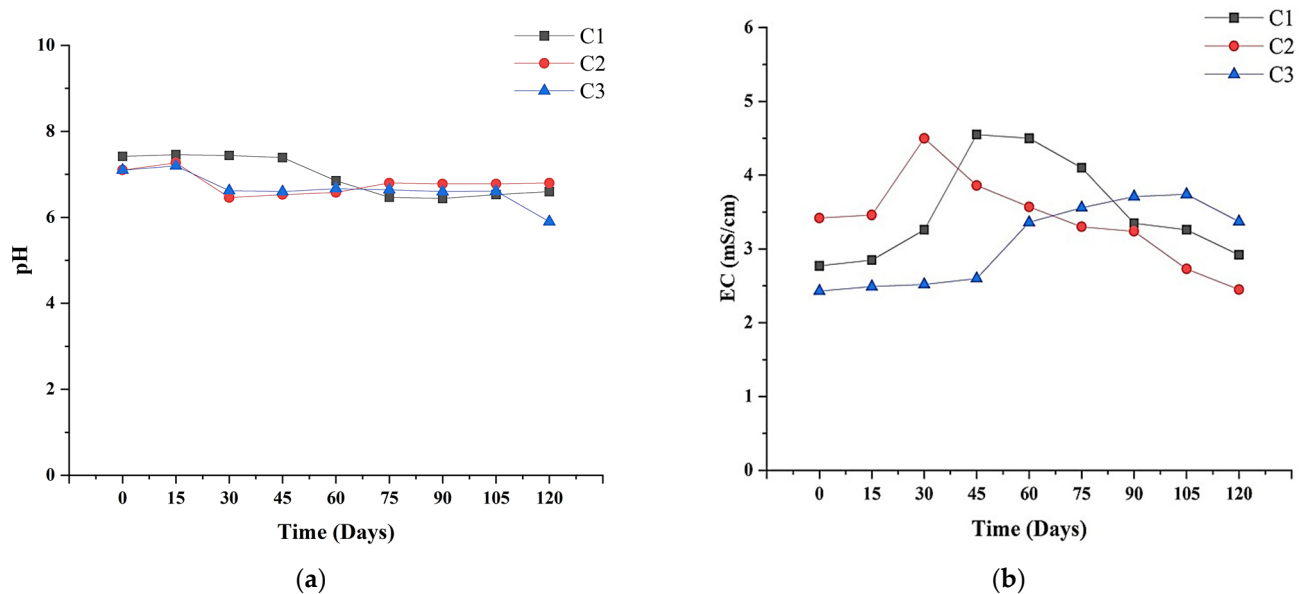


Figure 3. Temporal evolution of (a) pH and (b) electrical conductivity during the co-composting process.

EC serves as a critical metric denoting the concentration of soluble salts within compost, thereby reflecting the degree of OM mineralization [7]. Its significance in assessing compost quality is highlighted in prior literature [16]. As illustrated in Figure 3b, the EC measurements for C1, C2, and C3 initiated at 2.77, 3.42, and 2.43 mS/cm, respectively, and culminated at 2.92, 2.45, and 3.37 mS/cm, respectively. The co-composting progression initially escalated owing to OM mineralization during the mesophilic and thermophilic phases, subsequently declining towards the end of the process due to ammonia volatilization and the leaching of mineral salts [39–41]. Notably, the EC values recorded in this study align with the appropriate range for mature compost devoid of phytotoxic substances (less than 4 mS/cm) [42]. Interestingly, C2 exhibited the lowest EC value among the samples.

3.3. Elemental Analysis and Nutrient Levels

Throughout the co-composting process, the dynamics of OM and TOC reflect the biodegradation and transformation of organic substrates. Microbial activity drives the degradation of OM into more stable compounds (humic-like substances), resulting in reductions in the TOC and C/N ratio, alongside an increase in TN content [2]. The OM content in samples consistently declined as the composting process progressed. Notably, the final products of C1, C2, and C3 experienced respective losses of 61.26%, 33.74%, and 31.12% in their initial OM content (Figure 4a).

This reduction in OM corresponded proportionally to decreases in TOC and VS (Figure 4). Notably, the degradation rate of OM was higher and faster in C1 compared to C2 and C3, potentially due to the presence of easily biodegradable organic constituents [18]. Microorganisms play a critical role in metabolizing C and N for their cellular functions and growth [7], leading to a decrease in the C/N ratio. The C/N ratio serves as a key metric for assessing compost maturity in various studies [7]. In our experiment, the observed C/N ratios consistently remained below 20 (Figure 4d), consistent with guidelines set by the United States Composting Council (USCC) [43]. These experimental findings are in agreement with the prior research of [44], which observed a declining trend in the C/N ratio during GW composting, resulting in final ratios below 20. According to research by [45,46], the ratio of final C/N to initial C/N can evaluate compost maturation and OM stabilization, with an optimal threshold of <0.70, a criterion met in our study. As depicted in (Figure 5a), there is a contrasting trend observed in the ash content compared to that of TOC and OM.

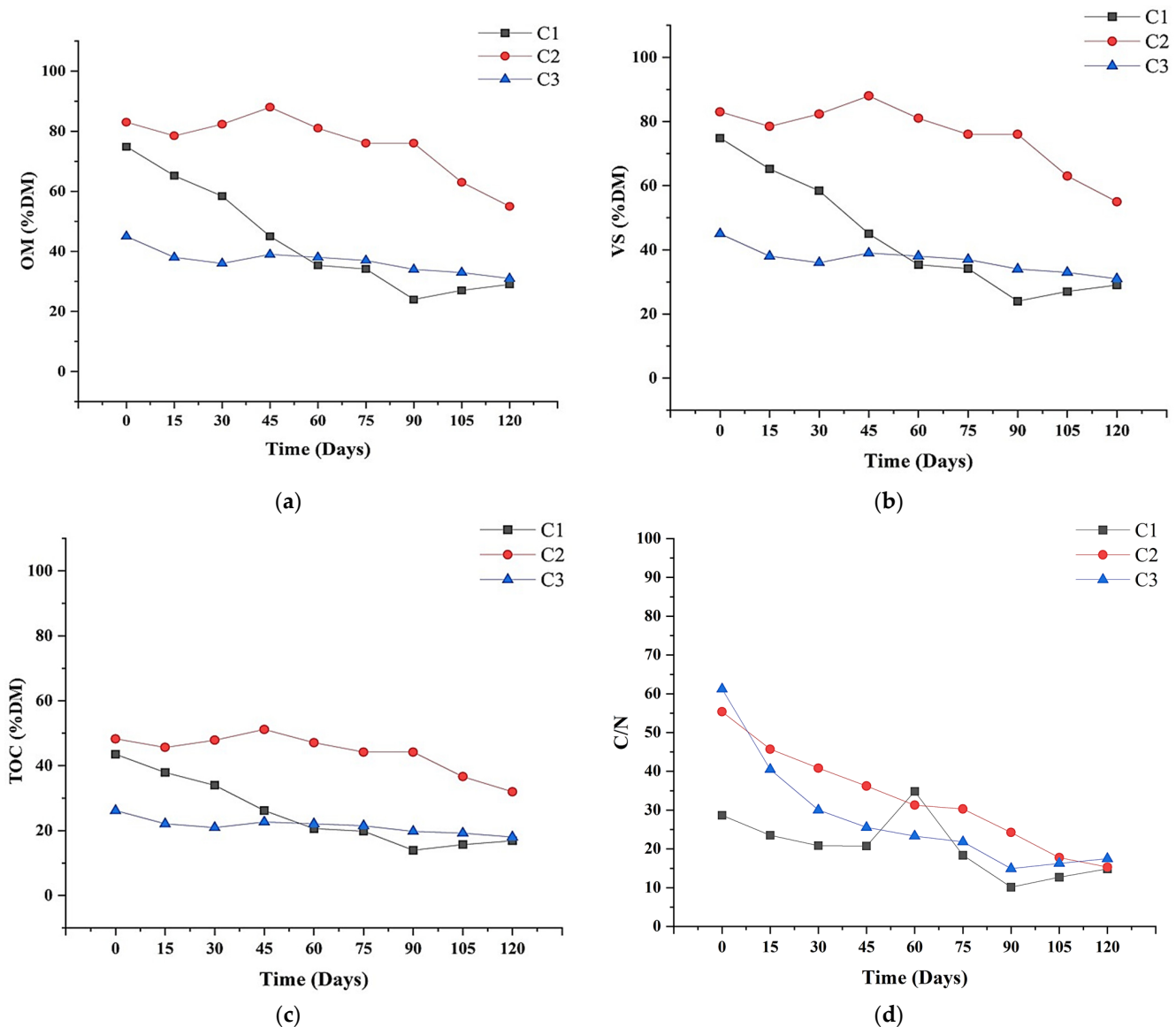


Figure 4. Temporal evolution of (a) organic matter, (b) volatile solid, (c) total organic carbon, and (d) C/N ratio during the co-composting process.

Initially, the ash content stood at 25.15%, 17%, and 55% in C1, C2, and C3, respectively. However, after 120 days, these values escalated to 71%, 45%, and 69%, respectively. This increase in ash content, as outlined in [1], serves as an indicator of accelerated degradation rates of GW. Alterations in TN content are linked to microbial activity [47]. Typically, N content undergoes an increase during composting, primarily due to the actions of nitrogen-fixing bacteria and the decomposition of OM and the loss of DM (Figure 5b) [1]. As illustrated in Figure 5c, the initial TN levels in C1, C2, and C3 were 0.81%, 0.91%, and 0.51%, respectively. Following 120 days of co-composting, these values escalated, reaching their highest levels by the end of the process, at 1.35%, 1.98%, and 1.02%, respectively. These results fall within the standard range for mature compost (0.5–2.5%) [9]. Notably, C2 exhibited the highest content among all the samples.

Phosphorus is recognized as a limiting nutrient in many agricultural soils utilized for crop cultivation and plays a vital role in fostering root development, enhancing seed production, and bolstering plant resistance [9]. Within the composting process, microorganisms utilize phosphorus for cellular development and growth [47]. As illustrated in Figure 5d, the TP content exhibited an upward trajectory during the experimental period,

primarily attributed to the loss of DM through OM degradation [7]. Despite phosphorus consumption by microorganisms during the process, it does not significantly impact the TP content. The initial TP levels observed in C1, C2, and C3 were 1.40%, 0.91%, and 0.30%, respectively. Over the 120-day co-composting period, these values increased, reaching peak levels of 2.90%, 3.22%, and 1.30%, respectively. Notably, C2 exhibited the highest TP content among all the samples. Furthermore, Mishra et al. [1] observed a similar increasing trend in P content during GW and cow dung co-composting.

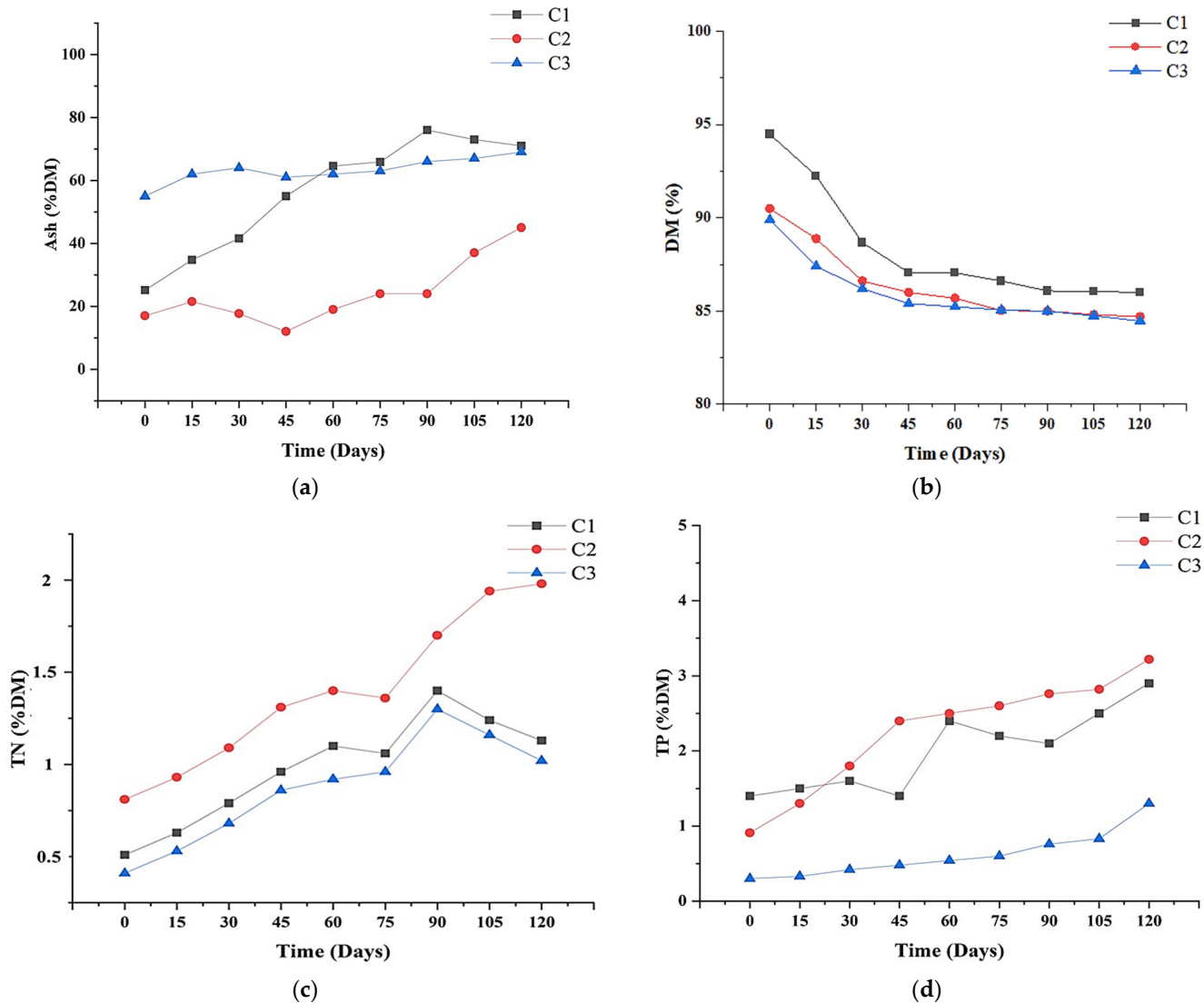


Figure 5. Temporal evolution of (a) ash content, (b) dry matter, (c) total nitrogen, and (d) total phosphorus during the co-composting process.

Ca and Mg are crucial nutrients that play significant roles in enzyme metabolism within seeds. As depicted in Figure 6, both Mg and Ca content exhibited an increase across all piles, albeit with varying percentages.

Initially, Mg content stood at 5.01%, 4.98%, and 3.19% in C1, C2, and C3, respectively, while Ca content was recorded at 4%, 1.45%, and 2.06% in the same piles. After 120 days of the bioprocess, the Mg content rose to 5.03%, 6.55%, and 4.87%, and Ca content increased to 10.21%, 11.37%, and 9.12% in C1, C2, and C3, respectively. Following standard values, all samples exhibited a Mg content exceeding 1.46% and Ca content surpassing 11.21%, rendering them beneficial for plant nutrition [48]. Importantly, C2 displayed the highest values among all samples. The observed increases in Mg and Ca content during composting

suggest efficient mineralization processes, potentially attributed to the breakdown of OM and the release of bound nutrients.

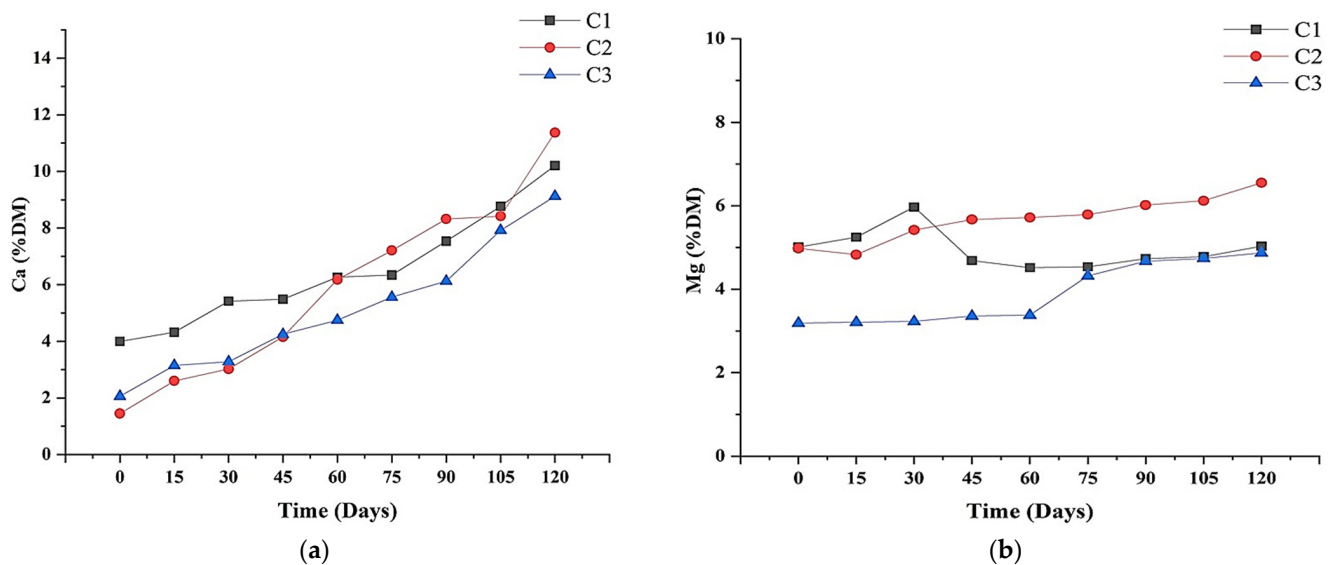


Figure 6. Temporal evolution of (a) calcium and (b) magnesium during the co-composting process.

K functions as a primary macronutrient vital for diverse physiological mechanisms in plants, encompassing critical processes such as photosynthesis and enzyme activation [7,49]. Its involvement in plant growth is extensive, influencing pivotal functions like CO₂ assimilation and water regulation. In contrast, Na is typically non-essential for most plant species, yet excessive Na levels can provoke toxicity, hampering plant development and vigor. Initially, the K contents in C1, C2, and C3 were documented at 0.23%, 0.45%, and 0.19%, respectively, while the Na concentration measured 0.19%, 0.31%, and 0.12%, respectively. Across the experimental timeline, the K content escalated to 0.49%, 0.61%, and 0.39% in C1, C2, and C3, correspondingly, while the Na content rose to 0.25%, 0.39%, and 0.25% in the same respective piles (Figure 7). Based on the findings, it is evident that C2 exhibits the highest concentrations of K and Na among the samples analyzed. These increments can be attributed to the mineralization of OM during the bioprocess, rendering K and Na available for microbial uptake and utilization.

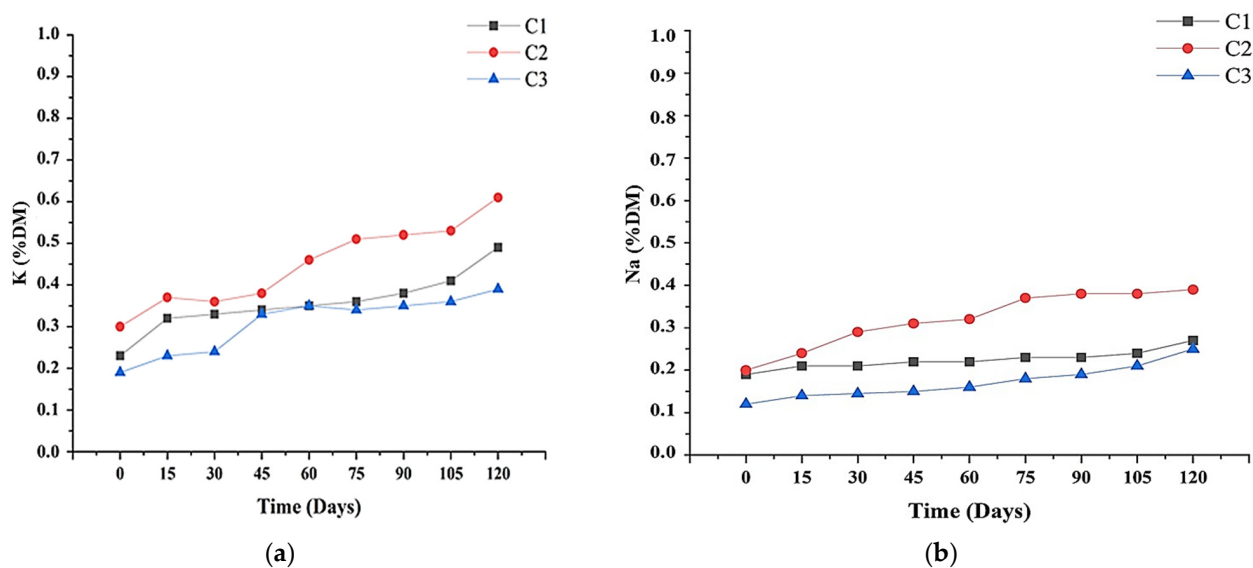


Figure 7. Temporal evolution of (a) potassium and (b) sodium during the co-composting process.

3.4. N-NH₄ and N-NO₃ Changes

Nitrogen plays a fundamental role in supporting plant growth and enhancing crop development. Within the composting process, nitrogen content serves as a key indicator of maturity, reflecting the quality of the end-product through the process of nitrification [47]. As illustrated in Figure 8a, the N-NH₄ concentration experiences an initial increase during the thermophilic phase, likely attributed to the ammonification process and the high microbial activity [50]. As the composting goes on, there is a decrease in N-NH₄ levels due to its conversion into N-NO₃, leading to a gradual accumulation of N-NO₃ (Figure 8b). All final values remain below 400 mg/kg, aligning with the recommended limit for N-NH₄ [51]. As mentioned in the literature, N-NO₃ is more readily utilized by plants compared to N-NH₄, underscoring the importance of achieving higher N-NO₃ levels in the final compost product [7]. The NH₄⁺/NO₃⁻ serves as an additional indicator of compost maturity [52]. In our experiment, the NH₄⁺/NO₃⁻ initially began at elevated levels and gradually decreased to less than 0.16, indicating the maturity of all the piles [53].

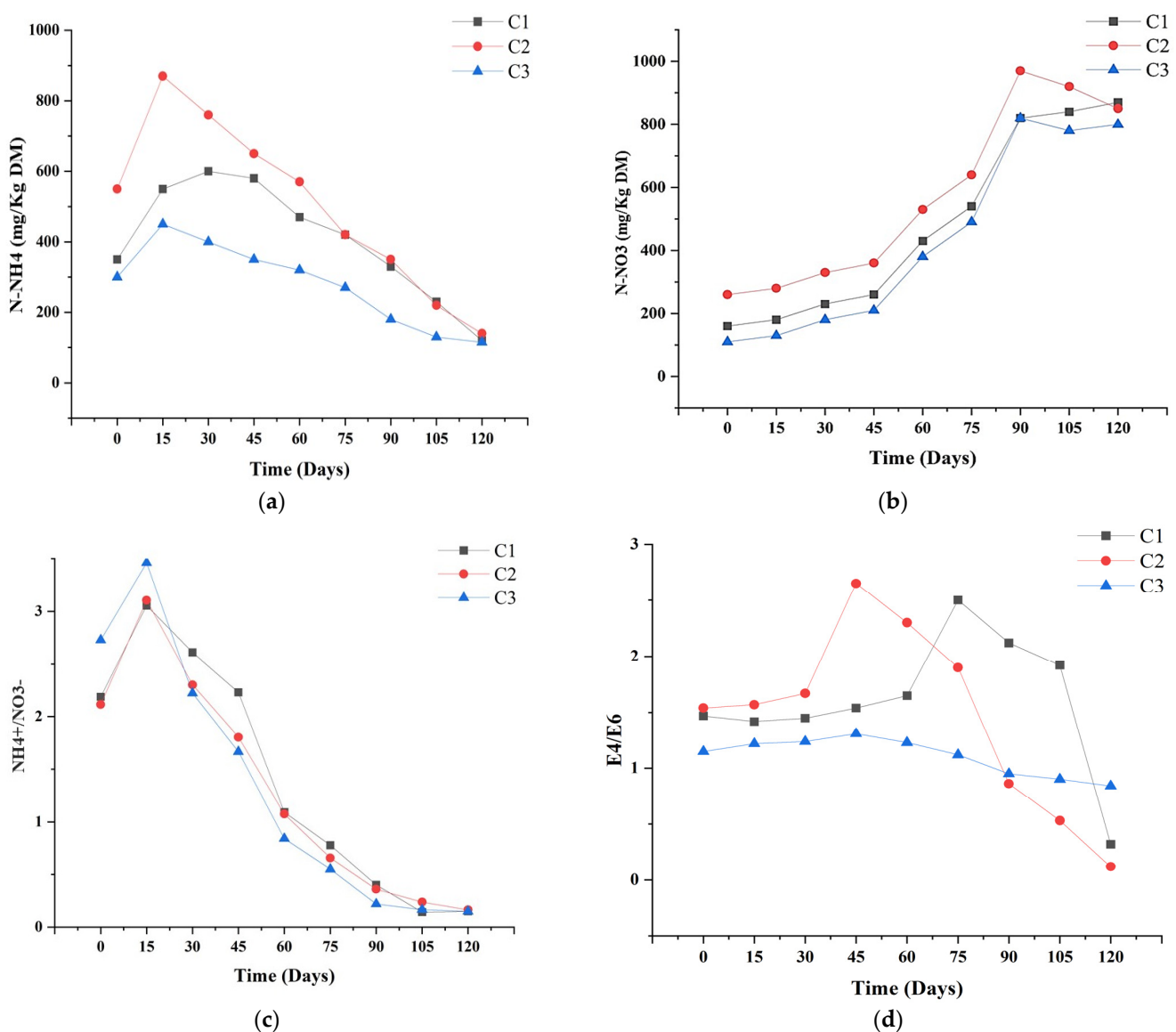


Figure 8. Temporal evolution of (a) N-NH₄, (b) N-NO₃, (c) NH₄⁺/NO₃⁻ ratio, and (d) E₄/E₆ ratio during the co-composting process.

3.5. Micronutrient Levels

Micronutrients play important roles in plant physiology, contributing to various biochemical processes crucial for growth and development. While micronutrients are present in smaller quantities compared to macronutrients like N and P, they still play essential roles in the composting process. Proper management of micronutrients during composting ensures their availability for plant uptake upon application of the compost as a soil amendment. However, excessive levels of certain micronutrients can lead to phytotoxicity, emphasizing the importance of balanced nutrient management in composting operations [54]. As observed in Table 3, it is evident that all piles exceeded the reference values except for C2, which demonstrated micronutrient levels suitable for promoting plant growth. Although Mn surpassed the recommended limit, Cu, however, was undetectable in all samples.

Table 3. Initial and final values of micronutrient in all piles.

Micronutrient	Units	Limit Values	Reference	C1		C2		C3	
				Initial	Final	Initial	Final	Initial	Final
Zn	mg/Kg DM	<100	[55]	119	132	52	83	98	112
Cu	mg/Kg DM	431–600		ND	ND	ND	ND	ND	ND
Fe	mg/Kg DM	<9300		478	580	211	321	324	357
Mn	mg/Kg DM	<200		266	315	223	230	130	232

ND: not detected.

3.6. Humification Index

During the composting process, fulvic acid (FA) serves as an intermediary in the formation of HA [18,56]. The E_4/E_6 ratio, considered as the humification index [57], corresponds to the ratio of optical densities of HA and FA at 465 and 665 nm, respectively. This ratio serves as an indicator of compost maturity [44], with a ratio of less than 5 indicating compost maturity and a ratio higher than 5 indicating compost immaturity [58]. As illustrated in Figure 8d, the E_4/E_6 ratio increased for C2 and C3 within the first 40 days, reaching its peak at Day 45, while C1 reached the highest values after 60 days. This increasing trend is attributed to the presence of FA and the low content of HA. However, as composting progresses, HA increases while FA decreases, resulting in a decrease in the ratio. The final values for C1, C2, and C3 were 0.32, 0.12, and 0.84, respectively, reflecting the maturity levels of the piles [59]. In comparison to the other compost samples examined, C2 demonstrated the lowest value.

3.7. Biological Parameters

GI serves as a sensitive biological indicator for assessing compost safety and its suitability for agricultural purposes [1,60]. Initially, the GI values for C1, C2, and C3 were approximately 32%, 42%, and 21%, respectively (Figure 9a). These values increased throughout the composting process, eventually exceeding 80% by the end. Notably, C2 displayed significantly elevated values (94.2%) relative to the other samples. Such high values indicate a safe substrate for plant growth, suggesting the suitability of the compost for agricultural use.

The respiration test serves as a valuable tool for evaluating composting performance and provides insights into compost stability and maturity from a microbiological basis. Initially, the respiration rate in all samples was low (Figure 9b). However, as the process progressed, this rate gradually increased, peaking during the thermophilic period. This increase indicates significant degradation of OM and high microbial activity. Subsequently, the respiration rate decreased, stabilizing at values of 5.00, 4.02, and 3 mg/50 g for C1, C2, and C3, respectively. The final values, reaching 5 mg/50 g or less, reflect the compost's stability [61], indicating that the end-product is sufficiently stable and suitable for agricultural purposes.

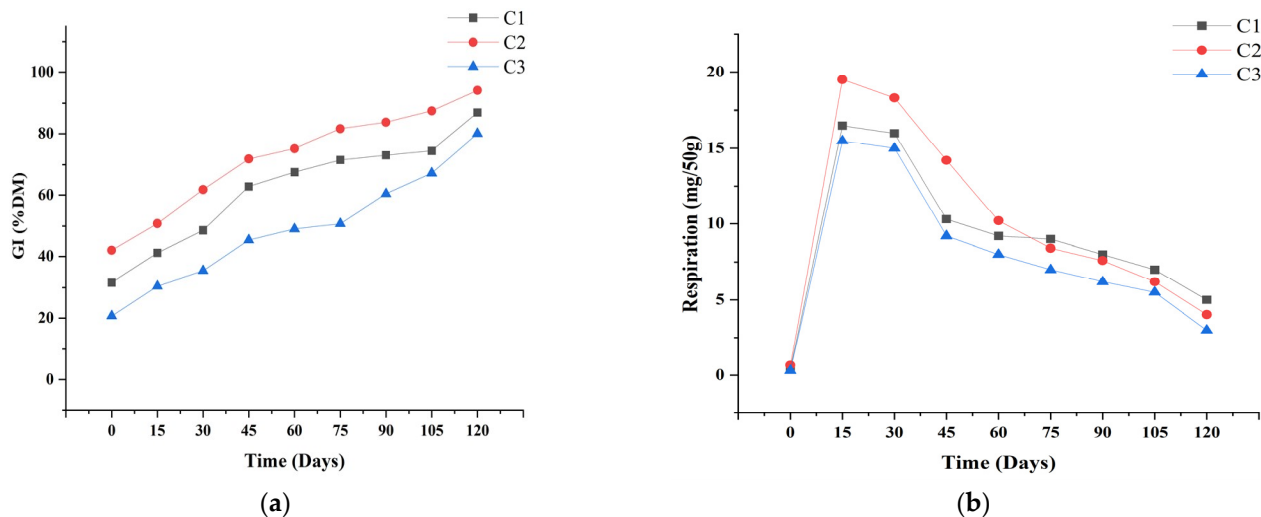


Figure 9. Temporal evolution of (a) germination index and (b) respiration rate during the co-composting process.

3.8. Statistical Analysis

3.8.1. The Correlation Studies between Various Physico-Chemical and Biological Parameters

The correlation analysis results reveal several important relationships between the studied variables (Table 4). Firstly, pH shows significant positive correlations with DM, OM, VS, TOC, and N-NH₄. However, it exhibits negative but non-significant correlations with CE, ash, TN, TP, K, Ca, N-NO₃, and GI. The EC demonstrates positive correlations with N-NH₄ ($r = 0.359$), respiration ($r = 0.201$), and GI ($r = 0.239$). DM is strongly positively correlated with N-NH₄ ($r = 0.705$), but shows non-significant positive correlations with OM, VS, TOC, and respiration. OM displays significant positive correlations with VS, TOC, TN, TP, K, Na, Mg, N-NH₄, and respiration. However, it exhibits negative correlations with ash content, Ca, N-NO₃, Fe, and Zn. For instance, the positive correlations between OM and various nutrient elements such as TN, TP, K, Na, and Mg suggest that the OM content influences nutrient availability in the compost. TN exhibits significant positive correlations with TP, K, Na, Mg, Ca, N-NO₃, Mn, and GI. TP shows significant positive correlations with K, Na, Mg, Ca, N-NO₃, Fe, Mn, and GI.

3.8.2. Principal Component Analysis

The PCA of various variables described the overall sensitivity pattern of the compost parameters and revealed the correlation between the variables based on the factor loadings from each principal component (PC). High-eigenvalue PCs were considered to represent the maximum variations among different compost properties.

The PCA loading for 20 variables allows the extraction of four principal components, explaining 90.15% of the overall variance of the data (Table 5).

The duo PC1–PC2 represents more than 75.01% of the data. Based on these percentages, the processes governing the physico-chemical and biological properties are essentially contained in these four components.

The PC1 accounts for 39.47% of the total variation, with large positive loadings of TN, TP, K, Na, Mg, Ca, N-NO₃, Fe, Mn, and GI. This suggests that PC1 represents a set of variables related to nutrient content and soil fertility in the compost. With high positive loadings of OM, VS, TOC, and N-NH₄, the PC2 explains 35.53% of the overall variance. With a high negative loading with ash content and Zn, PC2 likely represents variables associated with the organic composition and nutrient availability in the compost, with higher values indicating higher levels of organic matter and nutrient content.

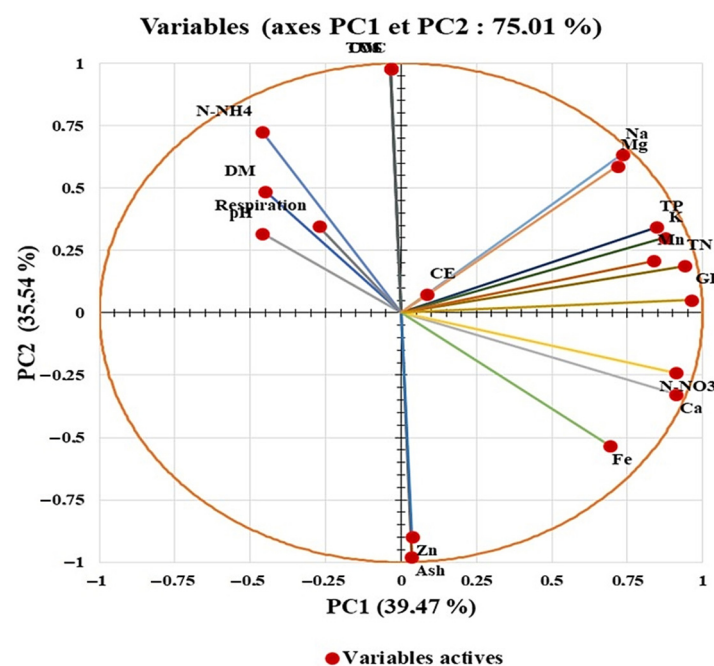
Table 4. Correlations coefficients among physico-chemical and biological parameters.

Variables	pH	CE	DM	OM	VS	Ash	TOC	TN	TP	K	Na	Mg	Ca	N-NO ₃	N-NH ₄	Fe	Zn	Mn	Respiration	GI
pH	1																			
CE	−0.207	1																		
DM	0.550	0.072	1																	
OM	0.311	0.014	0.400	1																
VS	0.311	0.014	0.400	1.000	1															
Ash	−0.311	−0.014	−0.400	−1.000	−1.000	1														
TOC	0.311	0.014	0.400	1.000	1.000	−1.000	1													
TN	−0.383	0.133	−0.345	0.140	0.140	−0.140	0.140	1												
TP	−0.231	0.132	0.058	0.264	0.264	−0.264	0.264	0.843	1											
K	−0.319	0.001	−0.343	0.256	0.256	−0.256	0.256	0.884	0.776	1										
Na	−0.136	0.021	−0.092	0.597	0.597	−0.597	0.597	0.794	0.794	0.871	1									
Mg	0.030	0.125	−0.020	0.558	0.558	−0.558	0.558	0.764	0.797	0.749	0.903	1								
Ca	−0.402	−0.043	−0.554	−0.349	−0.349	0.349	−0.349	0.772	0.674	0.691	0.463	0.498	1							
N-NO ₃	−0.572	0.046	−0.668	−0.244	−0.244	0.244	−0.244	0.811	0.611	0.736	0.530	0.491	0.879	1						
N-NH ₄	0.388	0.359	0.705	0.647	0.647	−0.647	0.647	−0.284	−0.062	−0.209	0.070	0.093	−0.671	−0.628	1					
Fe	−0.297	0.123	−0.358	−0.562	−0.562	0.562	−0.562	0.530	0.511	0.322	0.111	0.280	0.855	0.683	−0.611	1				
Zn	−0.104	0.031	−0.290	−0.886	−0.886	0.886	−0.886	−0.161	−0.206	−0.295	−0.585	−0.390	0.358	0.185	−0.604	0.670	1			
Mn	−0.159	0.101	0.076	0.120	0.120	−0.120	0.120	0.808	0.953	0.741	0.690	0.732	0.707	0.630	−0.140	0.612	−0.036	1		
Respiration	0.129	0.201	0.412	0.236	0.236	−0.236	0.236	−0.167	−0.022	−0.175	−0.026	0.021	−0.322	−0.362	0.705	−0.211	−0.266	−0.070	1	
GI	−0.523	0.239	−0.422	−0.005	−0.005	0.005	−0.005	0.909	0.836	0.863	0.724	0.681	0.853	0.859	−0.310	0.633	−0.038	0.801	−0.123	1

Table 5. Principal component analysis results of composts variables.

Variables	PC1	PC2	PC3	PC4
pH	−0.459	0.318	0.091	−0.679
CE	0.085	0.075	0.610	0.560
DM	−0.451	0.486	0.516	−0.393
OM	−0.034	0.978	−0.146	0.001
VS	−0.034	0.978	−0.146	0.001
Ash	0.034	−0.978	0.146	−0.001
TOC	−0.034	0.978	−0.146	0.001
TN	0.939	0.187	0.011	0.052
TP	0.846	0.343	0.269	−0.167
K	0.876	0.300	−0.152	0.049
Na	0.734	0.634	−0.128	0.003
Mg	0.717	0.588	0.066	−0.149
Ca	0.912	−0.326	0.010	−0.138
N-NO ₃	0.912	−0.241	−0.143	0.135
N-NH ₄	−0.460	0.725	0.445	0.175
Fe	0.691	−0.533	0.337	−0.222
Zn	0.037	−0.898	0.241	−0.218
Mn	0.837	0.208	0.330	−0.293
Respiration	−0.272	0.347	0.593	0.223
GI	0.962	0.051	0.117	0.175
Eigenvalue	7.895	7.107	1.713	1.315
Variability (%)	39.474	35.537	8.564	6.576
Cumulative (%)	39.474	75.011	83.575	90.151

PC3 accounts for 8.56% of the total variability in the dataset. It is characterized by significant positive loadings of CE, DM, and respiration. This component likely captures variables related to the physical and biological properties of the compost, such as conductivity, moisture content, and microbial activity. The PC4 explained approximately 6.57% of the total variance in the dataset. It is primarily characterized by a significant negative loading value for pH of -0.67 . PC4 may represent variables associated with acidity or alkalinity levels in the compost, with higher negative values indicating lower pH levels (Figure 10).

**Figure 10.** Principal component analysis for soil physico-chemical and biological properties.

3.9. Practical Implications of This Study and Future Research

As it is well known, gardens generate a substantial amount of nutrient-rich organic waste. Unfortunately, this precious resource is often incinerated rather than utilized, leading to the loss of potential benefits. This study addresses the challenge of effectively valorizing GW and SM through the composting process and assessing the quality of the end-product for agricultural applications.

Our research highlights the potentially pivotal role of composting in fostering environmental stewardship and promoting the circular economy, thus addressing pressing contemporary environmental concerns. As illustrated in Table 6, the findings indicated that the resulting compost (C2) has the highest quality properties and is characterized by the absence of phytotoxicity, which is pivotal for ensuring that the compost does not harm plant development.

Table 6. Final physico-chemical and biological properties of the co-composting end-products.

Parameters	Units	C1	C2	C3
pH	-	6.61	6.80	5.90
EC	mS/cm	2.92	2.45	3.37
OM	%DM	29.00	55.00	31.00
TOC	%DM	16.86	31.98	18.02
C/N	-	12.49	16.15	17.67
VS	%DM	29.00	55.00	31.00
DM	%DM	83.00	75.30	63.46
Ash	%DM	71.00	45.00	69.00
TN	%DM	1.35	1.98	1.02
TP	%DM	2.90	3.22	1.30
Ca	%DM	10.21	11.37	9.12
Mg	%DM	5.03	6.55	4.87
K	%DM	0.49	0.61	0.39
Na	%DM	0.25	0.39	0.25
N-NH ₄	mg/Kg DM	130.00	140.00	120.00
N-NH ₃	mg/Kg DM	870.00	850.00	800.00
Zn	mg/Kg DM	132.00	83.00	112.00
Fe	mg/Kg DM	580.00	321.00	357.00
Mn	mg/Kg DM	315.00	230.00	232.00
E ₄ /E ₆	-	0.32	0.12	0.84
GI	%DM	86.93	94.20	80.03
Respiration	mg/50 g	5.00	4.02	3.00

Additionally, this organic amendment has significant potential to enhance soil properties, including improving soil structure, increasing nutrient content, and boosting microbial activity [62].

In light of these findings, policymakers have the opportunity to promote the application of composting techniques by establishing legislation that encourages individuals and countries to use compost as an alternative and foster sustainable agriculture practices. This approach could provide an ecological solution for improving soil fertility in arid regions and impoverished soils [2], and it could also contribute to mitigating the adverse effects of climate change by enhancing soil carbon sequestration and reducing greenhouse gas emissions associated with waste incineration [63,64].

Moreover, this composting process results in a non-toxic by-product, which is safe for use in agriculture. This approach aligns with the principles of circular economy and supports the recycling process. By converting waste into a valuable product, such as compost, this perspective promotes environmental sustainability, resource conservation, and waste management.

This study demonstrated the feasibility of valorizing garden GW through co-composting with SM, producing compost that meets international standards and making it a viable option for improving soil health. However, to realize the maximum benefits of this co-

composting process, the availability of these materials must be facilitated through effective collection and sorting mechanisms. Policymakers should encourage waste collection initiatives through municipalities, communities, or the private sector. Emphasizing the importance of these operations can encourage the adoption of ecological practices and contribute to a more sustainable and environmental waste management system.

Future investigations could delve into several key areas to further enhance the understanding and the application of compost derived from GW and SM. One potential avenue of research is to assess the long-term effect of this co-composting end-product on the physical and chemical properties of soil including plant productivity over growing seasons. Further research could also investigate the microbiological activity of compost to ensure the absence of pathogens, as well as evaluate the presence of organic and inorganic pollutants that could potentially persist until the end of the process. Additionally, the optimization of composting conditions and duration could further enhance the efficiency of the global recycling system. Further research could also investigate the role of compost in the remediation of heavy metals-contaminated soils.

Exploring the effects of sunlight on the composting process warrants further exploration to deepen scientific understanding and refine composting practices. Assessing the economic feasibility of a large-scale composting process, along with its impact on soil and water quality, and overall biodiversity, will provide a comprehensive understanding of its potential economic and environmental benefits. Finally, studying the climate change mitigation potential will underscore the role of compost in sustainable waste management practices.

4. Conclusions

Organic waste valorization stands as a crucial strategy for safeguarding both human and environment health, while simultaneously reducing agricultural costs and minimizing the use of chemical products. Among various methods, composting emerges as a particularly effective biological, economical, and sustainable process for reusing OW materials. In line with this, the objective of our research was to comprehensively assess the stability, maturity, and development of composts derived from diverse combinations of GW and SM. Through the utilization of a wide array of physico-chemical and biological parameters, we aimed to delve into the intricacies of the composting process. This involved monitoring the composting progress over a period of 120 days, with regular sampling intervals of 15 days, utilizing three distinct types of GW: MGW, FL, and GC.

Our findings shed light on the significant transformation undergone during the composting process, marked by the absence of odors and insects and a transition to a dark brown coloration signifying maturation. Notably, C2 exhibited superior suitability for soil amendment compared to C1 and C3. This was evidenced by its favorable pH value of 6.80, electrical conductivity EC of 2.45 mS/cm, and OM content of 55%. Macronutrient analysis revealed TN, TP, and K values of 1.98%, 3.22%, and 0.61%, respectively, while the C/N ratio stood at 16.15. Importantly, the obtained compost demonstrated an absence of phytotoxic effects, with a high GI value of 94.20% and respiration rate of 5.05 mg/50 g, reflecting its stability and suitability for agricultural purposes.

Based on the findings of this study, several recommendations can be made to enhance the application and benefits of co-composting GW and SM. Firstly, the compost produced can be used to enhance the fertility of agricultural soils. Secondly, it could serve as a viable alternative to peat in greenhouse cultivation. Thirdly, utilizing this compost will support sustainable agricultural practices, and fostering innovation in composting technologies will further improve the impact and efficiency of composting efforts.

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