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Composting Urban Biowaste: A Potential Solution for Waste Management and Soil Fertility Improvement in Dolisie, Congo

Roche Kder Bassouka-Miatoukantama [1,2], Thomas Lerch [2,*], Yannick Enock Bocko [1], Anne Pando-Bahuon [2], Noël Watha-Ndoudy [3,4], Jean de Dieu Nzila [4] and Jean-Joël Loumeto [1]

[1] Laboratoire de Biodiversité, de Gestion des écosystèmes et de l'Environnement (LBGE), Université Marien Ngouabi (UMNG), Brazzaville BP 69, Congo; bassoukamiatoukantamar@gmail.com (R.K.B.-M.); loumeto@hotmail.com (J.-J.L.)
[2] Institute of Ecology and Environnemental Sciences of Paris, UMR 7618 (CNRS, SU, IRD, UPEC, INRAe, UPC), 94010 Créteil, France; anne.pando@ird.fr
[3] Institut National de Recherche Forestière (IRF), Ministère de l'Enseignement Supérieur, de la Recherche Scientifique et de l'Innovation Technologique, Brazzaville BP 177, Congo; nwathandoudy@gmail.com
[4] Laboratoire de Recherche en Géoscience de l'Environnement, Université Marien Ngouabi, Brazzaville BP 69, Congo
* Correspondence: thomas.lerch@u-pec.fr

Abstract: Population growth, urbanization, and changing consumption patterns are contributing to an increase in household waste production, particularly in sub-Saharan Africa. Composting of biowaste presents a sustainable solution by reducing the volume of waste sent to landfills while enriching the soil. The main objective of this study was to evaluate the suitability of solid household biowaste for composting in market garden crops in Dolisie (the Republic of Congo). Specifically, the study aimed to (i) assess the production and management practices of solid household waste in relation to socio-economic factors, (ii) analyze the chemical composition of solid household biowaste and its concentration of trace elements (TEs), and (iii) determine the potential phytotoxicity of solid household biowaste across different production seasons. In this study, wastes were collected from 40 households over a 60-day period, with daily sorting conducted during both the dry and wet seasons. Using a completely randomized design, various compost application rates were incorporated into the soil to conduct a germination test. The quality of the biowaste and compost was evaluated through physicochemical analyses. Results showed that approximately 90% of high-income households received regular waste collection services and practiced waste separation in contrast to middle- and low-income households. The composition of the biowaste was primarily composed of fruit and vegetable scraps, with slight contamination by chromium and cadmium. Temperature, pH, and humidity levels showed similar trends during compost formation in both the rainy and dry seasons. Germination rates were above 80% in all treatments across both seasons, indicating that the compost was mature. Overall, all physicochemical parameters of the compost met established quality standards, and trace element concentrations were below the recommended thresholds. The study concluded that biowaste, once converted into compost, can be safely applied to agricultural soils without posing any risk of phytotoxicity or contamination to crops.

Keywords: compost; solid household biowaste; socio-economic factors; physicochemical composition; trace elements; sub-Saharan Africa

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1. Introduction

Global waste production has been steadily increasing, rising from 300,000 tons to 7.5 million tons per day over the past century [1]. In 2016, global annual waste production was approximately 2.1 billion tons [2]. In sub-Saharan Africa, this volume is projected to double or even triple by 2050 [2]. Solid waste management has emerged as one of the most urgent and complex environmental challenges in recent decades. Rapid population growth, accelerated urbanization, and changing consumption patterns are driving the rise in waste production, exerting significant environmental pressures [3,4]. In large cities in the Republic of Congo, such as Brazzaville and Pointe-Noire, the political and economic capitals, waste management is a critical issue for city planners. The presence of unsightly waste piles and unauthorized landfills in urban areas has detrimental effects on both the environment and public health. Despite having the legal authority to manage waste, the municipality of Dolisie, the third-largest city in the country by population, faces significant difficulties in managing its waste [5,6]. Annual solid waste production in Dolisie is estimated at 17,550 tons [7]. With a low rate of household waste collection fees (TEOM), the municipality relies on state subsidies to provide waste management services [8]. Household solid biowaste constitutes up to 60% (10,530 tons per year) of the total waste produced, equating to around 3510 tons per year of compost. The average contribution of biowaste compost to agricultural soil is approximately 20 t/ha [9], which could potentially fertilize or amend up to 175 hectares of arable land, reducing the reliance on chemical fertilizers.

In this context, composting household solid biowaste for agricultural purposes presents a promising and effective solution to the contemporary challenges of waste management and environmental conservation [10–12]. This practice involves converting organic waste, such as food scraps, garden waste, and other organic materials, into compost—a valuable soil amendment that enhances soil quality and supports sustainable agricultural production [13–16]. By recycling nutrients and reducing landfill waste [17], composting serves not only as a means of attaining greener agriculture but also as a key strategy in the fight against global warming by reducing greenhouse gas emissions [18,19]. Through the principles of the circular economy, this approach demonstrates how natural solutions can complement intensive agriculture for sustainable resource management. However, market gardeners are often hesitant to use compost from household biowaste due to concerns over soil fertility management. Nevertheless, the use of compost from solid household biowaste is crucial for agricultural production [20,21]. When incorporated into soil, compost improves its structure and fertility, thereby enhancing plant growth [22]. Currently, no policies are in place to promote the valorization of solid household biowaste.

Before integrating compost into agricultural systems, it is essential to ensure that the compost is of good quality, meaning that it must be mature and stable [11,23]. The quality of compost depends on the composition of the biowaste [11,18]. A proper balance of carbon and nitrogen results in stable and nutrient-rich compost, whereas contaminants such as heavy metals and plastics can degrade the compost quality [18]. Thus, proper separation of biowaste is vital. It is evident that seasonal fluctuations can affect the production and composition of household waste, leading to significant variations in the physicochemical characteristics of the waste and the resulting compost [24]. These fluctuations are influenced by a variety of factors, including geographic location, climate, dietary habits, and cultural and religious events [25,26]. In addition to the carbon-to-nitrogen (C/N) ratio, factors such as pH, physical structure, aeration rate, temperature, and moisture content play critical roles in an efficient composting process [27,28]. Furthermore, biowaste and compost may be contaminated with pathogens and trace elements, which can lead to soil pollution and the contamination of agricultural produce. Nonetheless, composting biowaste contributes to a reduction in the levels of trace elements between the initial substrate and the final compost [29]. The decrease in trace metals in compost is influenced by bioavailability, microbial uptake, and leaching in an open system [30].

The overall objective of this study was to assess the suitability of solid household biowaste for use as compost in market garden crops in Dolisie, the Republic of Congo. Specifically, the study aimed to (i) evaluate the production and management practices of solid household waste in relation to socio-economic factors, (ii) determine the chemical composition of solid household biowaste and its concentration of trace elements (TEs), and (iii) assess the potential phytotoxicity of solid household biowaste depending on the production season.

2. Materials and Methods

2.1. Waste Management Practices According to Standard of Living and Season

This study was carried out in the town of Dolisie (12°40″ longitude East and 4°12″ latitude South) in the Niari department of the Republic of Congo (Figure S1). The town of Dolisie covers an area of around 100 km^2 and enjoys a low-Congolese climate, characterized by a dry season (June to September) and a rainy season (October to May). The average annual rainfall is around 1200 mm, and the average temperature is 25 °C [31]. The soil, predominantly ferralitic with a clayey texture, covers nearly 90% of the country's surface. The soil tested has low salinity and is poor in nutrients. It has a pH of 6.1 $\pm$ 0.1; the organic carbon content is 1.5 $\pm$ 0.1 and the C/N ratio is 9.7 $\pm$ 0.1. It degrades rapidly when subjected to mechanized cultivation with most crops [32]. In view of the wide diversity of living standards and eating habits among the populations living in Dolisie, the study area was subdivided into three living standards. Twenty households were considered in each standard, i.e., a total of 60 households made up the sample studied during the dry and rainy seasons. To assess the waste management practices of each household, a socio-economic survey was carried out to determine the amount of biowaste generated, the standard of living, waste management methods, the frequency of waste sorting at home, problems encountered in relation to waste, intervention measures, and the payment of household waste collection taxes (TEOM) in different types of households in the rainy and dry seasons.

Solid household waste was collected in two periods (from 15 February to 15 May 2021 for the rainy season and from 12 July to 30 September 2021 for the dry season). Beforehand, the bin bags were numbered, labeled, and deposited in each household thanks to the support of the Dolisie town council in partnership with the household waste pre-collection operators operating in the area. The bags were collected every day for 60 days during the rainy and dry seasons. The collected refuse bags were then transported by cart and unloaded at the household waste transit area for processing. Once in the household waste transit zone, the daily per capita quantity of waste produced by these households was determined on the basis of the ratio between the quantity of waste produced per day and the size of the household [33], and the waste was separated into three groups: biowaste, non-biodegradable waste, and special waste (Figure S2). The biowaste was divided into four parts, retaining its composition to form a homogeneous sample of at least 500 kg [34], and then classified into different sub-categories: food scraps, fresh fruit and vegetables, peelings, dead leaves, packaging leaves, green waste, and other organic residues (eggshells, wet paper, peanut shells, etc.).

2.2. Compost Processing Survey

Solid household biowaste was used to set up a composting system consisting of four 1.3 m heaps on each side and 1 m high (i.e., a surface area of 1.69 m^2), during the rainy and dry seasons (Figure S3). Each heap was watered, covered with a tarp and placed under a shed to avoid any external influences (sun, rain, etc.). The evolution of compost formation was monitored by measuring the temperature, pH, and humidity every three days to allow for aeration of the environment after the turning of the heap over a period of two months during the rainy and dry seasons. The temperature was measured using a probe thermometer at the end of the morning. The pH was measured using a pH meter in a solution prepared from 20 g of the sample taken (decomposing waste) in 100 mL of distilled water. The moisture content during the composting process was determined by drying a mass (100 g) of fresh compost at 105 °C in an oven for 24 h to create a constant dry mass.

2.3. Physicochemical Characteristics of Solid Household Biowaste

The pH was determined in the supernatant (residue/water ratio of 2:10) following 1 h of stirring. This measurement was conducted using a FiveEasy^{TM} FE20 pH meter (Mettler-Toledo, Columbus, OH, USA). Assimilable phosphorus and exchangeable bases (Na, K, Ca and Mg) were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS Agilent 7500 cx). The carbon (C) and nitrogen (N) content of the sample was determined by the Dumas method using a elementary analyzer (Flash HT, ThermoFisher, Waltham, MA, USA). Moisture content (H%) was determined from 100 g of a fresh sample dried at 105 °C in an oven to a constant dry weight. The total phosphorus and trace elements were determined using a S1 Titan X-Ray Fluorescence spectrometry (Bruker, Billerica, MA, USA). All these parameters were determined in solid household biowaste and compost samples according to the season.

2.4. Germination Test

The germination test was used to assess the phytotoxic effect of compost on the germinability of seeds from two species (beans, *Phaseolus vulgaris* L., Fabaceae, and, maize, *Zea mays* L., Poaceae). These species were chosen for their ability to withstand different doses of compost and to have relatively short germination times (3 to 5 days) at temperatures above 10–12 °C. A completely randomized set up with 4 blocks and 5 treatments (T0: soil only, T1: compost at 25% + soil at 75%, T2: compost at 50% + soil at 50%, T3: compost at 75% + soil at 25%, and T4: compost only) was set up during the rainy and dry seasons (Figure S4). One treatment corresponded to one pot (2 kg) containing 10 seeds of each species. Watering was carried out every two days to maintain humidity in each pot. Germination has been defined as the passage of a seed from a state of slowed life to a stage that brings the embryo to the threshold of active growth [35]. Each day, germinated seeds were counted manually for each species. The experiment ran for 10 days, as the germination time for beans and maize was 3 to 5 days. The germination rate (number of germinated seeds in each pot compared with the total number of seeds in the pot) was evaluated in each pot (treatment) and compared with the control pot for each species [36].

2.5. Statistical Analyses

Statistical analyses were carried out using R software (version R 4.1.2), with the PGIRMESS software packages being used for post hoc tests and "ggplot2" being used for the graphs. Given the non-normality and asymmetric distributions of the data, the ANOVA was performed using the non-parametric Kruskal–Wallis test for each variable considered. For the non-parametric Kruskal–Wallis test, the null hypothesis was "no difference between median for each variable". When the null hypothesis was rejected, we performed a post hoc Kruskal-Wallis multiple comparisons test on the median. To examine the evolution of the measured parameters (temperature, pH and moisture) as a function of time, an analysis of covariance (ANCOVA) was performed to test the effects of compost types between measured parameters and time (days). A single-criterion analysis of variance

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(ANOVA) was used to classify the quantitative variable (germination rate) against the qualitative variable (treatment) for each crop. All significant differences were reported at p-value < 0.05.

3. Results

3.1. Daily Production of Solid Household Waste

An analysis of variance showed statistically significant differences ($p < 0.001$) in daily per capita waste production between household types and within each household during the wet and dry seasons (Figure 1). High-status households produced 0.9 ± 0.3 kg/capita/day in the wet season compared with 0.7 ± 0.1 kg/capita/day in the dry season. In contrast, low-status households produced an average of 0.6 ± 0.1 kg/capita/day and 0.5 ± 0.1 kg/capita/day in the wet and dry seasons, respectively. The average daily production of solid household waste per inhabitant was 0.8 ± 0.2 kg/capita/day in the wet season and 0.5 ± 0.1 kg/capita/day in the dry season for middle-income households.

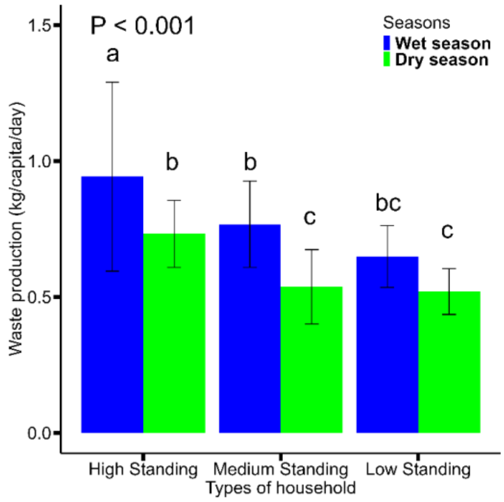

Figure 1. Daily production (kg/capita/day) of solid household waste in the wet and dry seasons. The error bars represent the standard deviation of the sample (n = 20). The different alphabetical letters on the graph indicate significant differences according to Tukey's test at $p < 0.001$.

3.2. Household Solid Waste Management Practices

The results show that high-income households had better access to waste collection services regardless of the season (Figure 2). Around 90% of these households benefited from regular waste collection by pre-collection operators. In contrast, only 3% of low-income households had access to the waste collection service in the rainy season, while only 1% had access in the dry season. Between these two extremes, 46% of middle-class households had access to waste collection in the rainy season, while 33% had access to it in the dry season.

However, low-income (low-status) households preferred illegal dumping (44–46%) and burning (21–43%) as waste disposal practices regardless of the season. As for middle-class households (medium standard), illegal dumping (17–23%), and burning (16–26%) were increasingly used as waste management methods regardless of the season. It should be noted that high-income households (upper middle class) also used landfills, nearby dumps, and burned some of their waste, but this did not affect the collection carried out by pre-collection operators. Depending on the season, middle-class and low-income households also used watercourses (1–8%), landfills (4–10%), nature (3–7%), and uninhabited plots (3–7%) as waste management methods.

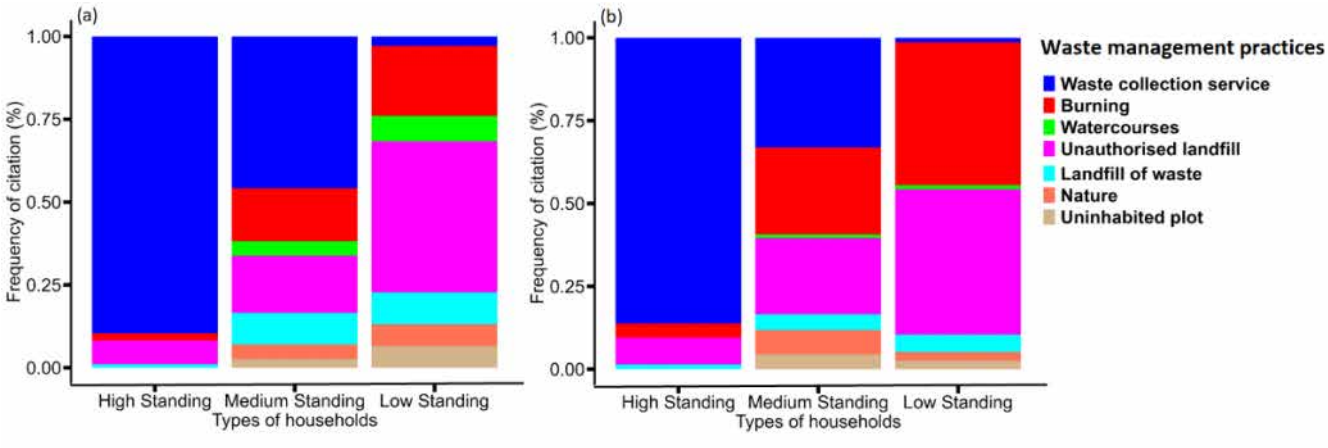

Figure 2. Household waste disposal practices in the wet (**a**) and dry (**b**) seasons in relation to people's standard of living.

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3.3. The Practice of Selective Sorting of Solid Household Waste

An analysis of variance showed statistically significant differences ($p < 0.001$) in the frequency of waste sorting by household type and between seasons for high-income households (Figure 3). High-income households sorted 36.9% of their household waste in the wet season and 44.8% in the dry season. Low-income households, on the other hand, practiced very little selective sorting of waste, with 0.9% being sorted in the wet season and 0.2% being sorted in the dry season. Middle-class households (medium standard) said they sorted a small amount of waste, around 10–13%, regardless of the season. Waste sorting, therefore, seems to be linked to people's standard of living and their knowledge of the value of waste.

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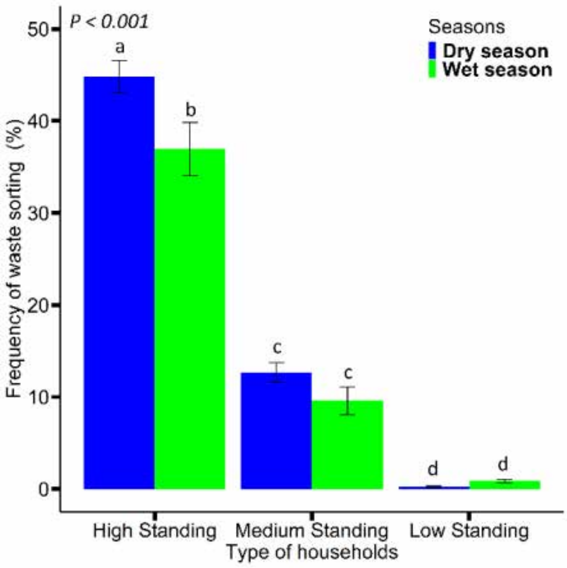

Figure 3. Practice of selective sorting of solid household waste in the wet (WS) and dry (DS) seasons. The error bars represent the standard deviation of the sample (n = 3). The different alphabetical letters on the graph indicate significant differences according to the Tukey test at $p < 0.001$.

3.4. Situation of the Household Solid Waste Management System

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The results of this study show that, whatever the season of the year, high- and middle-income households reported that the main problems encountered in relation to waste were threats to the environment (87–92% and 63–74%, respectively) (Figure 4a,b). In contrast, the low-income households surveyed reported having a minor amount of waste-related environmental problems (24–40%). To remedy this situation, regardless of the season of the year or the type of household surveyed, they considered the main intervention measures to be installing bins and/or a home waste collection service (64–81%), maintaining drains and roads (12–19%), and organizing community days (6–18%) (Figure 4c,d).

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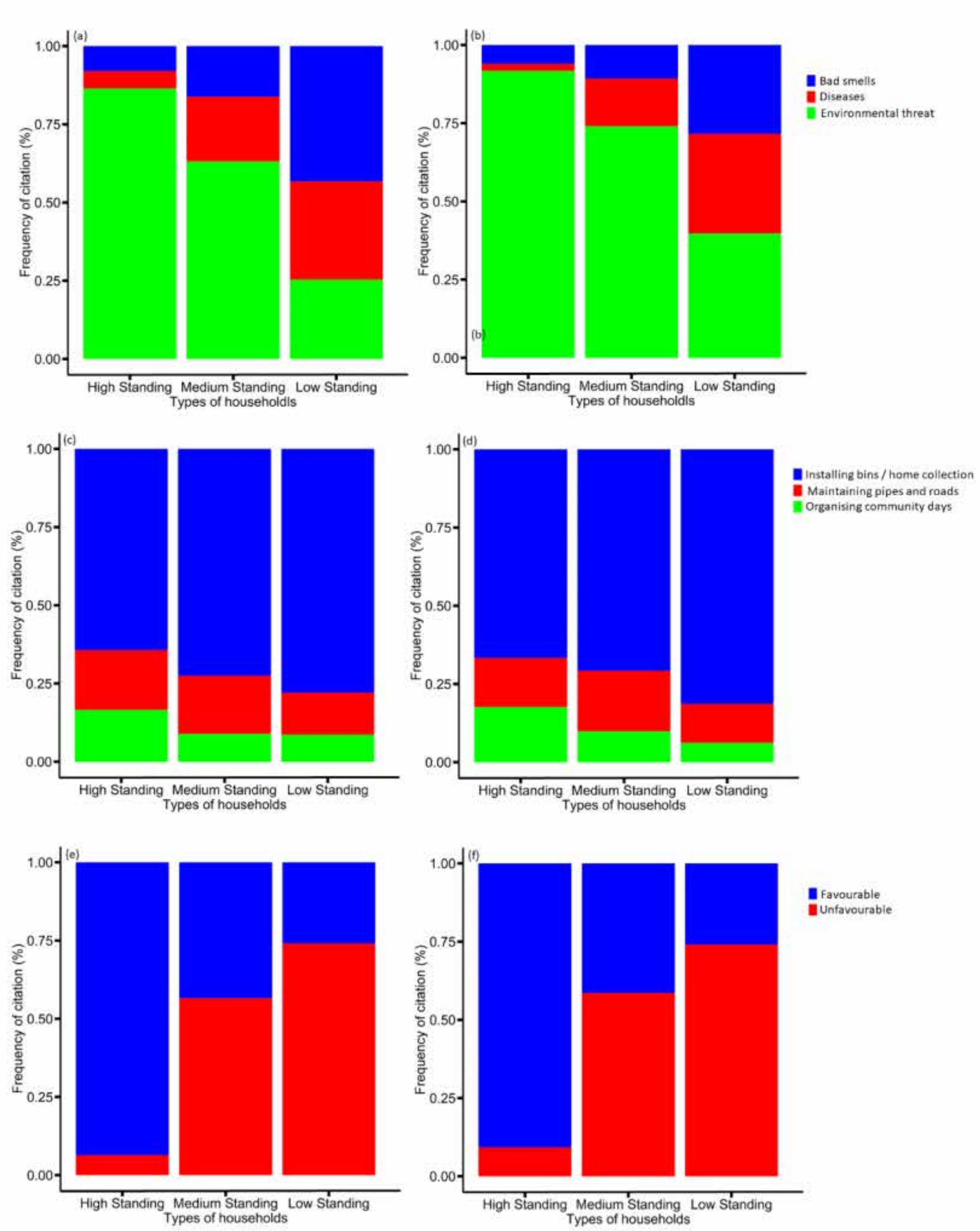

Figure 4. The situation regarding the solid household waste management system in Dolisie: responses based on the problems encountered, intervention measures, and payment of the household waste collection tax (TEOM) in the wet (**a**,**c**,**e**) or the dry (**b**,**d**,**f**) seasons, respectively.

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3.5. Composition of Solid Household Biowaste by Sub-Category

The composition of household solid biowaste in selected households in the ci Dolisie is divided into seven sub-categories, namely food scraps, fresh fruit vegetables, peelings, dead leaves, packaging leaves, green waste, and other or residues (eggshells, wet paper, peanut shells, etc.) (Figure 5). An analysis of var

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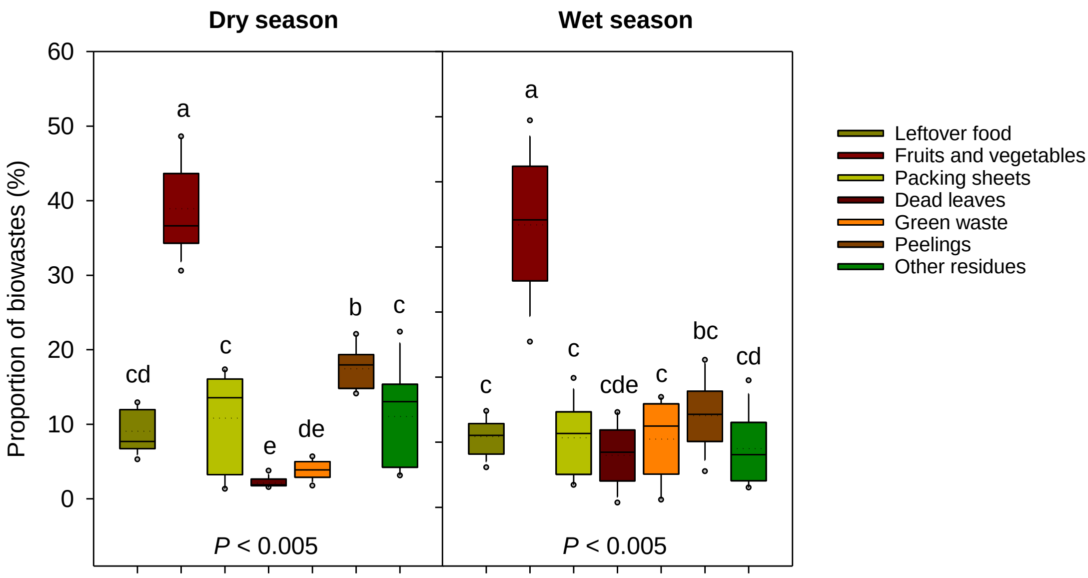

Figure 5. Characterization of household solid biowaste by subcategory during the wet season and dry season. Different letters on the graph indicate a statistically significant difference at $p < 0.05$ according to Tukey's t-test.

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3.6. Composting Process over Time

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The results show a similar evolution of pH and temperature during the composting process (Figure 6). On the other hand, there was a seasonal effect on the evolution of humidity during the composting process (p-value < 0.05). At the start of the experiment, the temperature varied between the wet season (35 ± 3 °C) and the dry season (29 ± 1 °C). A rapid increase in temperature was observed from the second week onwards, with peaks of 72 °C in the wet season and 70 °C in the dry season. After 60 days, the temperature fell from 30 ± 0.8 °C in the wet season to 29.3 ± 0.9 °C in the dry season (Figure 6a).

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An acid phase (pH < 7) was observed at the start of the composting process; the pH then increased during the first 30 days until it reached a peak of 9.3 in the dry season and was stabilized between 7 and 8 in both seasons at the end of the composting process (Figure 6b). Moisture content was observed and varied between 65 and 40% in both seasons (Figure 6c). The moisture content was 75.8 ± 9.2% in the wet season and 63.8 ± 4.0% in the dry season at the start of the composting process, decreasing to 37.6 ± 5.0% in the wet season and 34.6 ± 3.1% in the dry season at the end of the composting process (Figure 6c).

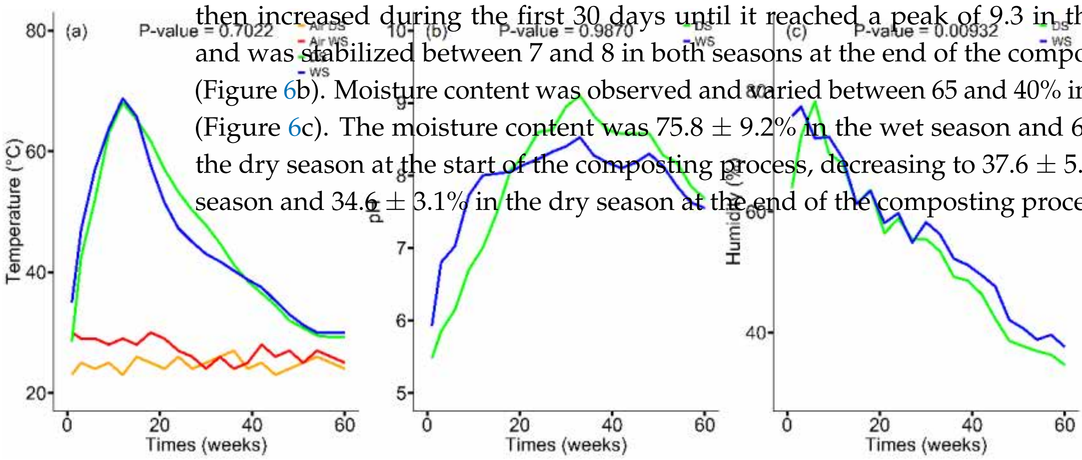

Figure 6. Variations in temperature (**a**), pH (**b**), and moisture (**c**) during the composting process

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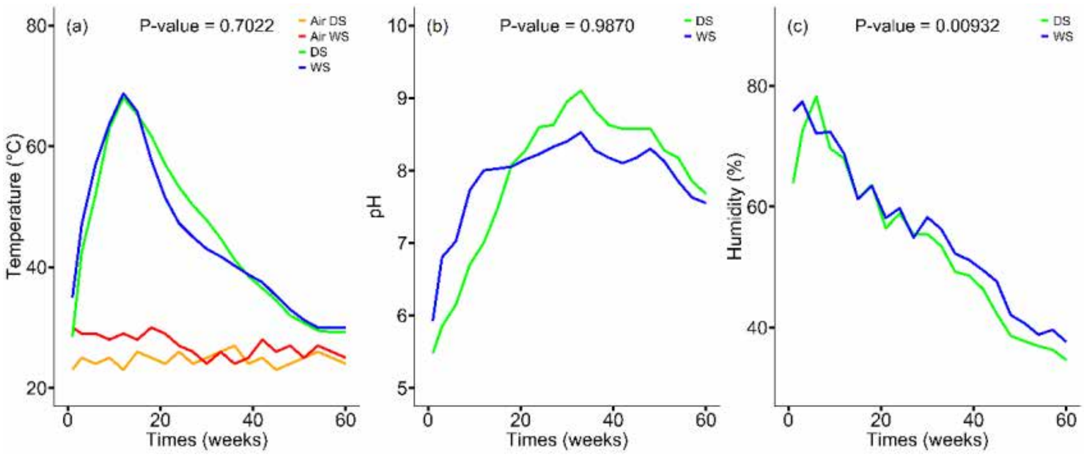

Figure 6. Variations in temperature (**a**), pH (**b**), and moisture (**c**) during the composting process during the wet season (WS) and dry (DS) season. The air temperature (air) is also shown for both seasons.

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3.7. *Physicochemical Quality of Biowaste and Compost*

Table 1 summarizes the physicochemical data obtained during the analysis of biowaste and compost from the town of Dolisie. An analysis of variance shows a seasonal effect on the majority of physicochemical data (p-value < 0.005) between biowaste and compost (Figure 7 left). However, there is no statistically significant difference (p-value > 0.05) in most of the physicochemical properties of biowaste and compost between the two seasons, except for magnesium, where a seasonal effect is observed (Table 1). Sodium (Na) and carbon (C) are much more present in biowaste than in compost, while mineral elements and pH show an increase in compost (Figure 7 left). The pH obtained in solid household biowaste is acidic, at 5.2 ± 0.1 and 5.0 ± 0.9 in the wet and dry seasons, respectively. On the other hand, the pH values obtained during compost maturation are between 6 and 9, which is characteristic of mature compost.

Table 1. Physicochemical characteristics of biowaste and compost produced in Dolisie. Values are the mean and standard deviation (n = 3). Significant effects of composting, season, and the interaction of the two factors are represented as followed: "***": $p < 0.001$; "**": $p < 0.01$; "*": $p < 0.05$. Different letters correspond to significant differences between the two seasons.

	Biowastes		Compost		Composting Effect	Seasonal Effect	Interaction
	Wet Season	Dry Season	Wet Season	Dry Season			
pH_{Water}	5.17 ± 0.11	5.02 ± 0.88	7.71 ± 0.03	7.66 ± 0.04	***	ns	ns
C_{Org} (%)	39.06 ± 4.05	34.82 ± 3.39	9.14 ± 0.45	10.52 ± 2.03	***	ns	ns
N (%)	2.42 ± 0.43	2.40 ± 0.36	0.97 ± 0.29	0.91 ± 0.03	***	ns	ns
C/N	16.34 ± 2.02	14.63 ± 1.60	10.06 ± 0.89	11.47 ± 3.61	**	ns	ns
P (%)	0.35 ± 0.25	0.37 ± 0.21	0.13 ± 0.04	0.08 ± 0.06	*	ns	ns
K (%)	1.81 ± 1.11	2.19 ± 1.29	0.44 ± 0.03	0.14 ± 0.28	***	ns	ns
Na (%)	0.03 ± 0.01	0.02 ± 0.01	0.08 ± 0.01	0.09 ± 0.03	***	ns	ns
Mg (%)	0.99 ± 0.39 ^{a}	0.91 ± 0.22 ^{b}	0.07 ± 0.01 ^{b}	0.12 ± 0.01 ^{a}	***	ns	***
Ca (%)	2.39 ± 1.29	2.12 ± 1.18	0.33 ± 0.04	0.30 ± 0.01	***	ns	ns
Moisture (%)	75.77 ± 9.00	63.82 ± 4.00	37.61 ± 5.00	34.62 ± 3.00	***	ns	ns

The moisture content of biowaste is higher in the wet season (75.8 ± 9.0%) than in the dry season (63.8 ± 4.0%) due to the high consumption of fresh fruits and vegetables and food waste. In biowaste, the C/N ratio averaged 16.3 ± 2.0 in the wet season and 14.6 ± 1.6 in the dry season. After two (02) months of aerobic composting, the average C/N ratio was 10.06 ± 0.89 in the wet season and 11.5 ± 3.6 in the dry season. There was a significant decrease (p-value < 0.05) in compost compared with biowaste. The levels of organic carbon, total nitrogen, and organic matter in biowaste obtained during the wet and dry seasons were 39.1 ± 4.1 to 39.06 ± 4.1%, 2.4 ± 0.4 to 2.4 ± 0.4%, and 67.2 ± 6.9 to 59.9 ± 5.8%, respectively. Nutrient content (P, K, Mg, Ca and Na) decreased significantly (p-value < 0.05) in compost compared to biowaste. A between-class analysis performed on chemical properties clearly showed the differences between biowastes and compost (Axe 1 = 73% of explained variability), with a decrease in Corg and Na concentration being found upon composting (Figure 7). The seasonal effect only explained 6% of variability (Axe 2), with a slight increase being seen in the K content and pH levels.

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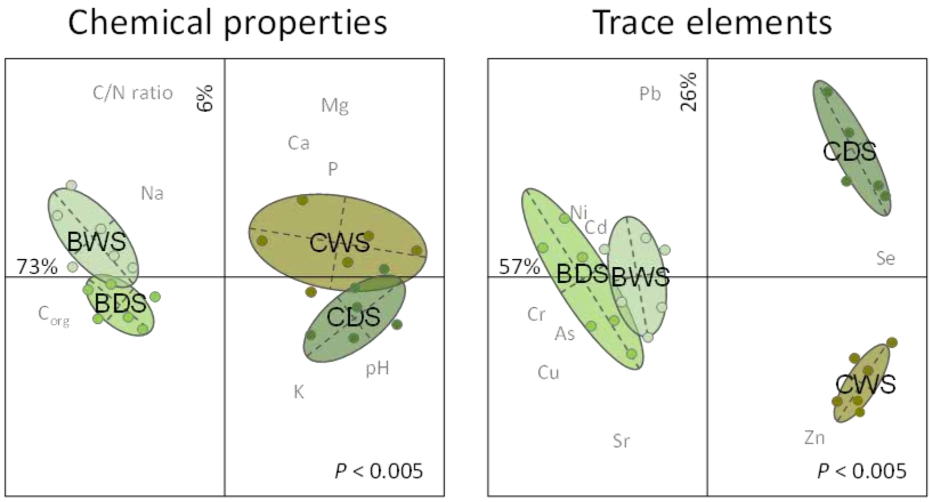

Figure 7. A between-class analysis (BCA) performed on chemical properties and trace element composition among biowastes and compost. The ellipses represent 60% of the variability. Letters represent the barycenter of the replicates (n = 6) for biowastes collected during dry (BDS) or wet (BWS) and composted during dry (CDS) or wet (CWS) season. Monte Carlo test simulated p values (lower left corner) revealed significant differences among treatments.

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3.8. Trace Metals in Biowaste and Compost

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The results of this study show that the trace content of most of the elements determined in biowaste and compost was influenced by the season, except for lead (Pb) and strontium (Sr) (Table 2, Figure 7 right). In addition, an analysis of variance showed statistically significant differences (p-value < 0.05) for arsenic (As) and copper (Cu) levels in biowaste and for copper, strontium, and zinc (Zn) in compost. Nickel (Ni), chromium (Cr), cadmium (Cd), arsenic (As), and copper (Cu) were more present in biowaste than in compost (Figure 3 right). However, high values of cadmium (5.5 ± 1.3 to 5.5 ± 3.6 mg/kg) and chromium (185.0 ± 25.1 to 194.4 ± 11.8 mg/kg) were observed in the wet and dry seasons, respectively, for biowaste exclusively. A between-class analysis performed on a trace element composition revealed a significant difference between biowaste and compost samples (Axe 1 = 57% of explained variability), with a decrease in most of the TEs except Zn and Se. While biowaste showed a similar composition in terms of TEs regardless of the season, the Axe 2 (26% of explained variability) revealed significant changes between composted materials with higher Pb content in the dry season and higher Zn content in the wet season.

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Table 2. Trace element concentrations (ppm) of biowaste and compost produced in Dolisie. Values are the mean and standard deviation (n = 3). Significant effects of composting, season, and the interaction of the two factors are represented as followed: "***": $p < 0.001$; "**": $p < 0.01$; "*": $p < 0.05$. Different letters correspond to significant differences between the two seasons.

	Biowastes		Compost		Composting Effect	Seasonal Effect	Interaction
	Wet Season	Dry Season	Wet Season	Dry Season			
As	7.58 ± 0.42 [b]	9.06 ± 1.43 [a]	5.63 ± 1.49	6.25 ± 1.19	***	*	ns
Cd	5.50 ± 1.29	5.48 ± 3.51	2.76 ± 0.47	2.83 ± 0.46	**	ns	ns

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Cd	5.50 ± 1.29	5.48 ± 3.51	2.76 ± 0.47	2.83 ± 0.46	**	ns	ns
Cr	185.03 ± 25.05	194.35 ± 11.77	70.13 ± 17.98	93.25 ± 20.47	***	ns	ns
Cu	42.45 ± 2.01 [b]	48.03 ± 3.42 [a]	28.63 ± 4.25	33.50 ± 3.87	***	**	*
Hg	<LOD	<LOD	<LOD	<LOD	/	/	/
Ni	10.85 ± 3.58	13.68 ± 3.75	5.11 ± 1.34	5.06 ± 2.88	***	ns	ns
Pb	20.41 ± 2.57	19.58 ± 5.29	19.63 ± 5.12	15.75 ± 1.94	ns	ns	ns
Se	9.18 ± 1.75	9.13 ± 0.48	2.10 ± 0.12	2.00 ± 0.47	***	ns	ns
Sr	147.08 ± 52.43	119.28 ± 52.65	124.38 ± 12.90 [a]	63.50 ± 16.02 [b]	ns	ns	***
Zn	353.18 ± 114.13	312.60 ± 73.59	81.63 ± 24.87 [b]	169.50 ± 20.58 [a]	***	ns	***

3.9. Germination Test

The results of this study show that bean and maize seeds germinate in three-phase curves (Figure S3 in Supplementary Materials). The latent phase (phase 1) refers to the period during which the seeds do not germinate. The absence of germination during this phase is due to water absorption by the seeds and the synthesis of enzymes essential for the basic metabolism of germination. In general, this first three-day phase corresponds to the time taken for the radicle to pierce the seed coat. The second phase is characterized by the germination of seeds (beans and maize) with a remarkable evolution of the germination rate. It begins from day 4 to day 7 of the experiment. This phase is characterized by increased metabolic activity and leads to the emergence of the embryonic radicle, which in turn exploits the reserves contained in the culture medium. The third phase begins on day 8 and ends at the end of the study. This phase is characterized by a constant germination rate marking the end of seed germination (Figures S5 and S6). The germination rate was ≥60% for all treatments and species studied in both seasons. There was a statistically significant difference (p-value < 0.05) in the germination rates between treatments according to time, but no effect (p-value > 0.05) dose was observed in regard to the germination rate. The germination test for bean and maize seeds in biowaste compost was >90% characteristic of mature compost.

4. Discussion

4.1. Waste Management Practices According to Standards of Living and Season

The results indicated that the majority of high-income households subscribe to the waste collection service provided by the TPOs operating within the city. In contrast, low-income households primarily engage in uncontrolled dumping (44–46%) and burning (21–43%) as waste disposal practices, which aligns with findings of Kaza et al. [2] but differs from the studies of Ssemugabo et al. [37] in Kampala, Uganda, and Chikowore [38] in Zimbabwe. This discrepancy may be attributed to the irregularity and quality of waste collection services. Inefficient waste management services are likely to result in the open dumping of solid waste within residential areas, as observed by Chikowore [38]. Regardless of the season, high- and middle-income households identified environmental threats as the primary waste-related issue, as reported by Jagun et al. [39], whereas low-income households reported fewer environmental concerns. This difference may be due to the varying levels of education among household heads regarding waste management practices [39]. For instance, the use of inadequate waste storage facilities in residential areas exposes residents to flies and unpleasant odors, which adversely affect both the environment and public health [40].

Additionally, the results show that more than 90% of high-income households are willing to pay waste collection fees regardless of the season. In contrast, middle-income households are divided on whether they should pay a waste collection tax to the local authorities. In the metropolitan city of Bharatpur, Nepal, Rai et al. [41] found that households do pay taxes for waste collection. However, low-income households are reluctant to pay the TEOM due to the perceived lack of cleanliness in the city. This variation in willingness to pay may be linked to factors such as awareness of the health and environmental impacts of waste, socio-economic status, the quality of the waste collection service, and its perceived sustainability. Households that pay the waste collection tax typically spend less than one US dollar per trip, which is consistent with the findings of Ssemugabo et al. [37]. Public authorities should focus on improving access to waste management services and encourage households to utilize them.

The daily production of household waste per capita varied by season, with an average of 0.79 ± 0.19 kg/inhabitant/day during the rainy season and 0.59 ± 0.12 kg/inhabitant/day during the dry season, in line with the findings of Gómez et al. [42] in Mexico. These results differ from those of Topanou et al. [34], who reported that waste production in Abomey-Calavi, Benin, was not significantly influenced by climate, although minor fluctuations were noted. Conversely, Denafas et al. [43] observed that daily waste production tends to be higher in the dry season, potentially due to activities such as spring cleaning and the seasonal disposal of unwanted items. In some cities, a portion of recoverable material from household waste is diverted for agricultural or livestock purposes, which can reduce per capita waste production [44,45]. Higher-income households generally produce more waste compared to medium- and low-income households, a trend also noted by Gómez et al. [42] in Mexico. This reduction in daily waste generation can be explained by differences in lifestyle, dietary habits, socio-economic conditions, and household size [46]. Waste management practices are influenced by various socio-economic factors, including population density and urbanization, which necessitate more advanced waste collection systems in urban areas. Furthermore, the availability of infrastructure and the effectiveness of public policies directly influence population behavior regarding waste management. Cultural perceptions of waste, including viewing it as a resource, and the economic activities prevalent in the area also play a role in shaping waste management practices.

4.2. The Chemical Composition of Solid Household Biowaste and Compost

This study demonstrated significant differences in the subcategories of household solid biowaste within each season and between seasons. Fresh fruits and vegetables constituted the largest subcategory of household solid biowaste in both the wet and dry seasons [47,48], likely reflecting the increasing demand for fresh produce, which results in an abundance of organic waste in household garbage bins. In contrast, the composition of household solid biowaste in Shone, Ethiopia, is predominantly composed of food scraps [49]. This production is often associated with multi-family households in both urban and rural settings [50]. Food and kitchen scraps are typically the primary components of household solid biowaste, as cooking and eating are the central activities in most households [51]. Green waste, on the other hand, represents the smallest proportion of household solid biowaste. Although not directly generated by households, it still contributes significantly to the overall waste composition, often ending up in garbage cans, bins, and landfills.

At the onset of the experiment, temperature differences were observed between the rainy and dry seasons. A rapid increase in temperature was noted from the second week, reaching peaks of 72 °C during the rainy season and 70 °C during the dry season. This temperature rise is attributed to the microbial degradation of easily decomposable organic matter [52,53]. After 60 days, the temperature gradually decreased, likely due to a reduction in microbial activity and the depletion of readily degradable organic waste [52,54]. For pH, an acidic phase (pH < 7) was observed at the beginning of the composting process as a result of the organic acids produced during the degradation of organic matter [47,51,55]. The pH gradually increased over the first thirty days, reaching more alkaline values and stabilizing between 7 and 8 by the end of the composting process in both seasons [56,57]. This increase in pH is attributed to the degradation of the initial organic material, including the breakdown of proteins and amines, and the production of ammonia during the ammonification process [58,59]. The initial pH of the solid household biowaste was acidic, measuring 5.17 ± 0.11 in the wet season and 5.02 ± 0.88 in the dry season [60], which can be attributed to the organic acids produced by fruits, vegetables, and food scraps [47,51]. However, the pH of the biowaste used for composting was slightly alkaline [61], possibly due to the biowaste composition. In contrast, pH values during compost maturation ranged from 6 to 9, which is characteristic of mature compost [40]. A study by Oviedo-Ocaña et al. [62] reported an alkaline pH in compost derived from biowaste in small municipalities in Colombia. This discrepancy may be explained by the consumption of protons during the degradation of volatile fatty acids, the production of CO_2, and the mineralization of organic nitrogen [63,64].

The moisture content in biowaste was higher during the wet season compared to the dry season due to the increased consumption of fresh fruits and vegetables and food waste [65]. Moisture content was influenced by the nature of the solid household biowaste, the location of production, and the social conditions of the producers [48,66]. Throughout the composting process, moisture content ranged from 40 to 65%, which is favorable for optimal microbial activity [67]. In contrast, the moisture content ranged from 40 to 45% during the composting of biowaste in Lomé, Togo [53]. Low moisture levels at the beginning of the composting process can lead to accelerated dehydration, thereby halting microbial activity and resulting in a physically stable but biologically unstable compost [68]. The observed differences can be attributed to the presence of aerobic microorganisms and the heterogeneity and quality of the composted organic waste. Moisture content during maturation decreased from 37.61 ± 5.00% in the wet season to 34.62 ± 3.00% in the dry season, reflecting a smooth composting process [69].

Chemical analyses revealed that sodium (Na) and carbon (C) were present in higher concentrations in the biowaste than in the compost, while mineral elements and pH levels increased in the compost. The decrease in the carbon-to-nitrogen (C/N) ratio during the composting process is an indicator of compost stability and maturity [58]. A C/N ratio close to 12 is frequently regarded to indicate fully mature compost [70]. The levels of organic carbon (39.1 ± 4.1% to 39.06 ± 4.1%), total nitrogen (2.4 ± 0.4% to 2.4 ± 0.4%), and organic matter (67.2 ± 6.9% to 59.9 ± 5.8%) in the biowaste during the wet and dry seasons indicate that it is an excellent soil amendment for vegetable production [71–73]. Despite composting, the carbon (9.1 ± 0.4% to 10.5 ± 2.0%), nitrogen (0.9 ± 0.3% to 0.9 ± 0.1%), and organic matter (15.7 ± 0.8% to 18.1 ± 3.5%) contents in the compost indicate that it is a high-quality fertilizer for agricultural soils [74,75]. The reduction in carbon, nitrogen, and organic matter from biowaste to compost is attributed to the turning and aeration of the compost heap [76] and microbial activity during the composting process [77–79]. Nutrient content (P, K, Mg, Ca, and Na) significantly decreased (p-value < 0.05) in the compost compared to the biowaste [80]. This decrease may be due to the diminished rate of oxygen uptake during the composting process, which limits substrate availability and reduces microbial activity in mature compost [81].

4.3. Trace Element Content and the Phytotoxicity Potential of Compost

The trace element content in biowaste and compost has been the subject of several studies [60,61,82,83] and is a critical parameter for evaluating its suitability as an agricultural soil amendment. The results of this study show statistically significant differences ($p < 0.05$) in the levels of arsenic (As) and copper (Cu) in biowaste and copper (Cu), strontium (Sr), and zinc (Zn) in compost. These differences can be attributed to factors such as the quality of organic matter, production location, and climatic conditions [29,66]. Nickel (Ni), chromium (Cr), cadmium (Cd), arsenic (As), and copper (Cu) were found in higher concentrations in biowaste compared to compost. This reduction in TE content during composting is attributed to bioavailability, microbial absorption, and leaching processes within an open composting system [30]. When compared with international standards (e.g., FAO and AFNOR), which regulate the quality of organic substrates for agricultural use, most TE concentrations were below the regulatory limits, except for cadmium and chromium, which exceeded the limits in biowaste during both the wet and dry seasons.

The high chromium levels in biowaste are believed to stem from leather products and certain metal alloys found in the household solid waste stream [84–87], while batteries and electronic devices are the primary sources of cadmium contamination [87,88]. Biowaste used for composting or as agricultural inputs can contain heavy metals such as cadmium (Cd) and chromium (Cr), which pose potential risks to human health and environmental quality [20,21]. When biowaste containing chromium and cadmium is applied to agricultural soils, it can harm plant growth and have adverse effects on both human and animal health. For example, cadmium is toxic even at low concentrations, bioaccumulating in the kidneys and causing renal and bone dysfunctions, and it is classified as a carcinogen by the International Agency for Research on Cancer [89,90]. Similarly, hexavalent chromium (Cr^{6+}) can cause respiratory irritation, lung cancer, dermatitis, and systemic damage [91,92]. These heavy metals can also contaminate food crops and groundwater when present in composts derived from biowastes [20,21]. Effective management practices, including selective sorting, compost analysis, and decontamination technologies, are critical for mitigating these risks and protecting human health [2]. Furthermore, heavy metals can inhibit microbial activity under both aerobic and anaerobic conditions [93]. However, the composting process itself can help stabilize these TEs through the use of specific additives [94]. During active microbial degradation in the composting process, water-soluble TEs can be reduced by adding organic and inorganic additives such as bamboo charcoal, biochar, fly ash, phosphate rock, lime, or zeolite [83,95,96]. In the current study, TE levels in the final compost were found to be below international standards [82,97]. For example, the levels of Zn and Pb obtained in the compost were lower than those reported in compost produced in Togo [52]. The NF U 44-051 standard, which governs the toxicity thresholds of TEs in organic amendments, sets the limit for chromium at 120 mg/kg and for cadmium at 3 mg/kg. While zinc, copper, and nickel are required in small quantities in compost, higher concentrations can lead to soil accumulation, inhibit plant growth, and contaminate the human and animal food chains [98,99]. Analyses of organic waste have revealed that the concentrations of certain elements can exceed the maximum allowable thresholds in raw waste but remain within acceptable limits for compost. To address this issue, promoting the source separation of waste by the population is essential. Awareness campaigns and training seminars targeting local communities are vital to engaging all socio-economic groups and fostering more sustainable organic waste management practices.

Composting, while an effective method for biowaste valorization, presents several technical challenges, particularly in managing temperature and moisture, which are critical parameters for ensuring efficient and hygienic decomposition. Maintaining an optimal temperature range (40–70 °C) is essential to promoting thermophilic microbial activity and eliminating pathogens. However, this was often compromised by climatic fluctuations, especially between the rainy and dry seasons. The quality of the biowaste also played a significant role, with factors such as dry matter content and moisture levels directly influencing compost formation. The biowaste used in this study was highly humid, which slowed microbial activity and hindered the rapid temperature rises. To mitigate this, the compost piles were aerated by turning every three days, and dry materials were added to maintain optimal moisture levels (40–70%) during both the mesophilic and thermophilic phases. These challenges necessitated rigorous monitoring and frequent adjustments, such as aeration, dry material addition, and regular parameter checks, to ensure a successful and sustainable composting process.

Compost maturity is a key factor in assessing compost quality [49,57]. Various methods exist for evaluating maturity, but there is no single test that can comprehensively assess this criterion. Field assessments of compost quality often involve pH measurement and the germination test. The results of this study show that bean and maize seeds germinated according to a three-phase curve [36], with an absence of germination being found during phase 1 due to water absorption by the seeds and the synthesis of enzymes necessary for germination metabolism [100]. The germination rate for both bean and maize seeds in biowaste compost was greater than 90%, indicating the compost's maturity [101]. Germination rates are strongly influenced by seed type [102,103]. In general, compost is considered non-toxic when the germination rate exceeds 50% [52]. The absence of phytotoxic compounds in compost is linked to its maturity and the duration of the composting process [104]. The seasonal variations observed in this study did not significantly influence the phytotoxic quality of the compost, suggesting that the composting process was successfully completed [67,75].

5. Conclusions

Waste management practices in Sub-Saharan African cities are often characterized by inadequate collection systems, limited biowaste valorization, a reliance on informal sector actors, and significant socio-economic disparities. These challenges; however, also offer opportunities for developing sustainable solutions tailored to local contexts. In Dolisie, Congo, the present study revealed that approximately 90% of high-income households benefitted from regular waste collection services provided by pre-collection operators and engaged in household waste sorting, a practice less common among medium- and low-income households, with seasonal variations occurring in participation. High- and medium-income households identified environmental threats as the primary waste-related issue, and they viewed the installation of bins or the provision of regular waste collection services as the most effective interventions. Over 90% of high-income households expressed a willingness to pay for household-waste removal taxes, whereas low-income households were reluctant to pay the local waste tax, citing the unsanitary conditions prevailing in the city. Solid household waste production in Dolisie was consistent with the average daily waste generation observed in other Sub-Saharan African countries. Household solid biowaste production in Dolisie was categorized into seven subcategories, with fresh fruits and vegetables being the dominant waste type across all seasons. These biowastes were slightly contaminated with chromium and cadmium, which rendered them unsuitable for direct application to agricultural soil. However, this study demonstrated that composting significantly reduced these contaminants to levels below the recommended thresholds. Monitoring of temperature, pH, and humidity during the composting process indicated typical variations consistent with a well-managed composting process without seasonal fluctuations. The final compost produced was of good quality and could be safely applied to agricultural soil (approximately 175 hectares) without risk of toxicity or plant contamination. To ensure the continuous availability of organic matter for sustainable compost production, the establishment of an efficient waste management system is crucial. Additionally, implementing a waste-sorting system would help minimize the contamination of solid household biowaste with trace elements (TEs).

A long-term assessment of the impact of compost on soil fertility and crop yields across diverse agro-climatic zones is recommended to assess the feasibility of this practice. This requires establishing experimental plots in various agro-climatic zones to evaluate the effects of compost on soil fertility and agricultural productivity. Key parameters to monitor will include organic matter content, nutrient availability (N, P, K), soil biological activity, and crop yields over multiple cropping cycles. These data will enable the quantification of cumulative effects and the identification of optimal soil amendment practices. Furthermore, a soil and compost quality monitoring program should be established, with regular assessments of soil quality after compost application, focusing on indicators such as soil structure, water retention capacity, and microbial biodiversity. Concurrently, systematic analyses of the compost should be conducted to ensure compliance with quality standards, particularly regarding contaminants (beyond TEs, including organic pollutants or pathogens). Establishing local partnerships for training and awareness is also essential. Collaborations with farmers, researchers, and policymakers should be fostered to integrate field feedback with scientific observations. Training programs on the sustainable use and management of compost should be organized, and platforms for sharing results and adapting agricultural practices should be established to maximize long-term agronomic benefits. Raising awareness and engaging local communities are critical for the effective implementation of waste management and valorization services. These communities play a central role in the organization, planning, and success of urban waste-management initiatives, ensuring alignment with current national regulations. Their involvement will lead to improved coordination, increased public awareness, and better adherence to best practices, ultimately ensuring the sustainable and responsible management of waste.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17020560/s1. Figure S1. Study area in the Republic of Congo showing the 12 departments (a), Niari department showing the city of Dolisie (b) and experimental sites (c). Figure S2. Waste sorting for the valorization of biowaste through composting. © Bassouka-Miatoukantama, 2021. Figure S3. Degradation of organic matter during the composting process: (a) initial pile, (b) pile after four weeks, (c) pile after six weeks and (d) mature compost at eight weeks. © Bassouka-Miatoukantama, 2021. Figure S4. Experimental germination test device. Treatments: T0: soil only, T1: compost at 25% + soil at 75%, T2: compost at 50% + soil at 50%, T3: compost at 75% + soil at 25%, and T4: compost only. Figure S5. Germination rates of bean seeds (a: wet season and b: dry season) and corn (c: wet season and d: dry season) from different treatments (T0: soil only. T1: compost 25% + soil 75%; T2: compost 50% + soil 50%; T3: compost 75% + soil 25% and T4: compost only). Figure S6. Phyto-toxicity test of compost obtained with corn (a) and bean (b) seeds following different compost doses.

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