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Research

Quantification and valorization of compost derived from urban households' waste in Bukavu City, Eastern D.R. Congo

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Abstract
This study focused on quantifying and valorizing domestic waste in Bukavu, a rapidly growing city in eastern Democratic Republic of Congo (DRC). With increasing anthropogenic pressure, waste management has become a pressing issue, yet documentation in this area is still limited. This study aimed to fill this gap by providing comprehensive data on domestic waste generation, composition, and disposal practices in Bukavu city. Through field surveys and analysis, waste quantities and types were documented, revealing significant challenges in waste management infrastructure and practices. Additionally, the study explores opportunities for waste valorization, particularly through composting, given the region's agricultural potential and growing urban food demand. The findings revealed that ~ 5% of the domestic waste is biodegradable, with the majority consisting of metals and plastics. These wastes are predominantly used as livestock feed (10%), incinerated (66%), or buried (17%), with ~ 5% undergoing composting. Waste management is primarily handled by children (82%), with very few non-governmental organizations (NGOs) involved in such activities. Among the three composting methods evaluated, outputs from vermicomposting demonstrated superior qualities in terms of promoting crop growth, increasing yield, and achieving a high germination index. Overall, the application of composts improved plant growth and yield parameters of the two major legumes (common bean and soybean). Future interventions should explore the implementation of large-scale composting units at the household or citywide level, while also considering additional strategies to enhance the quality of the compost products. Such efforts are crucial in mitigating the environmental and health impacts of urban household waste and promoting sustainable practices in urban agriculture.

Keywords Composting methods · Urban waste management · Biodegradation · Nutrients · Leguminous crops · Urban agriculture

Abbreviations

OM	Organic matter
DRC	Democratic Republic of Congo
TN	Total nitrogen

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TP	Total phosphorous
C/N	Carbon to Nitrogen ratio
DAS	Days after sowing
CRD	Completely randomized design
LSD	Least significant difference of means
ANOVA	Analysis of variance
GI	Germination index
Vermi	Vermicompost (or Lombricompost)
CV	Coefficient of variation
GHG	Greenhouse gas
SDG	Sustainable development goals

1 Introduction

The rapid growth of the global human population, particularly in developing countries, has led to severe environmental degradation and pressure on forests, water resources, and biodiversity [1–5]. Effective waste management in cities and towns worldwide is a pressing challenge, as the lack of proper treatment and disposal methods for both biodegradable and non-biodegradable waste exacerbates the problem [6]. It is crucial for researchers and decision-makers to address this issue and develop sustainable waste management strategies, particularly in African cities, including those in the sub-Saharan African region, to mitigate environmental impacts and improve the well-being of local populations [5–7].

In the Democratic Republic of Congo (DRC), cities and towns are facing significant population growth, resulting in the generation of large amounts of waste [8, 9]. The lack of waste treatment and recycling facilities has led to severe degradation of water and air quality, negatively impacting the well-being of the population [9]. This situation is exacerbated by economic challenges, poverty, and political conflicts, which hinder the establishment of proper waste management systems [9]. In Bukavu, a major city in the South-Kivu province, the absence of waste management infrastructures has resulted in water and air contamination, posing a significant health risk [10–12]. Improper waste disposal leads to various issues such as unpleasant odors, poor air quality, mosquito breeding, and traffic congestion, exacerbating conflicts among households [10]. The increased exposure and lack of preventive measures have contributed to the rise in diseases like cholera, diarrhea, malaria, and typhoid fever [11–13]. To address these challenges, local organizations and entrepreneurs have initiated small-scale projects for waste recycling, focusing on the production of charcoal bricks and paving materials [14]. Inappropriate waste disposal practices can have detrimental effects on the ecosystem by introducing pathogens, inorganic salts, and hazardous trace metals into the soil, as well as releasing greenhouse gases [14]. It is imperative to find sustainable technologies that can enhance the value of waste materials and mitigate these environmental issues.

Many initiatives of biodegradable domestic waste management included anaerobic digestion for subsequent digestate (liquid fertilizer) use in horticulture, biochar production for subsequent crop fertilization, and use as substrates for mushroom production. One alternative for valorizing waste is through composting, which has gained momentum as a waste management technology, particularly in developing countries [15–18]. Composting offers a sustainable approach with a limited environmental footprint and the potential to improve soil quality through organic nutrient sources [19]. Vermicomposting, a form of composting that involves using earthworms to break down organic matter, is particularly popular, promotes soil enhancement on poor, and degraded agricultural lands [20, 21]. However, while valorizing waste as compost; the mineral composition of the final products can vary depending on the methods used, thus affecting crop responses [20–22].

Urban agriculture, including horticulture, livestock, fishing, forestry, and milk production, is becoming increasingly important in urban and periurban areas [23–25]. It provides fresh food, job opportunities, waste recycling, green spaces, and enhances urban resilience to climate change [26]. Composting methods play a role in integrated soil fertility management (ISFM), providing essential nutrients, humic acids, growth hormones, beneficial microbes, enzymes, and vitamins to meet crop requirements [26, 27]. These organic fertilizers are crucial for improving degraded agricultural soils and increasing crop yields, particularly in regions with limited biomass production and soil degradation, such as in Sub-Saharan African cities and towns [28, 29]. Composting methods offer a means to enrich nutrient and carbon content in degraded soils, promote sustainable urban agriculture, and enhance food security in these regions with poor waste management and agroecological practices.

In Bukavu City in the South-Kivu province, issues related to waste management are currently observed, and yet there is limited documentation on the topic, making livelihood conditions difficult. In this city, urban and periurban agriculture continues to expand, providing a potential opportunity of value-addition to household waste through composting. Organic waste composting could reduce the dependence on neighboring cities or towns for food supply, particularly in terms of vegetables and legumes [29]. There has been a growing interest in urban agriculture projects as a means of promoting agro-ecological farming transition. These projects encompass various aspects such as sustainable food supply, social connections, community well-being, participatory initiatives, environmental education, and landscapes. Composting household waste not only holds promise as a recycling method but also as an effective waste management solution. This process sanitizes household waste and transforms it into humus within a relatively short period. Composting, in its various forms, aims to produce high-quality compost that can serve as a valuable source of essential nutrients for crops, thereby improving the physical and chemical properties of soils [30–32]. The use of compost products to meet the organic matter requirements for fertilizing crops and amending soils is particularly advantageous from an economic standpoint, given the high cost and limited availability of mineral fertilizers in Sub-Saharan Africa regions, and in eastern DRC particularly [27, 33]. To address these objectives, the following key research questions were formulated: (i) how is the management of biodegradable waste conducted in the Bukavu city? (ii) What is the composition of the compost produced from organic waste, and which composting method exhibits the greatest agricultural potential? (iii) Do these compost products enhance the growth and productivity of the two major leguminous crops?

The overall aim of this study was to contribute to the local recycling of urban household waste through composting methods, with a focus on improving nutrient availability for urban crop production. Specifically, this study aimed to (1) characterize the urban waste generated by Bukavu households, (2) evaluate the impact of three local composting methods on the physicochemical availability of nutrients, and (3) assess the effects of the obtained composts on the growth and productivity of two major leguminous crops.

This study, like many others emerging recently, addresses the issue of waste management in developing countries. Its uniqueness lies in being one of the first to be conducted in the eastern region of DRC, highlighting the value of the final product, the compost, in agricultural production. This is particularly relevant given the growing food demand in the cities and urban centers of eastern DRC, one of the most densely populated regions in the country, if not the continent.

2 Materials and methods

2.1 Study area

Domestic wastes were collected from Panzi and Nguba, two agglomerations from the Ibanda municipality, in the southern and western areas of the Bukavu City, respectively. The experiments to evaluate the composting methods and analyze the compost were conducted at the Faculty of Agriculture and Environmental Sciences of the Université Evangélique en Afrique (UEA) in Panzi-Ibanda municipality, Bukavu, South-Kivu province, eastern DRC. Both trials for common beans and soybeans were conducted in a greenhouse at an elevation of ~ 1594 m above sea level (m.a.s.l), with a latitude of 02°54’15” (South) and longitude of 028°36’34” (East).

Bukavu, with an area of ~ 44.3 km^2, is divided into three municipalities: Bagira, Kadutu, and Ibanda. The city has a humid tropical climate influenced by its altitude and its proximity to the Lake Kivu. According to the Köppen-Geiger classification, the climate is categorized as AW3 type, with a dry season lasting three months and a wet season lasting nine months (Supplementary material 1). The annual rainfall is generally high, reaching around 1542 mm, and the average temperature is ~ 21.0 °C. Formerly known as the "green city" and "the Switzerland of Africa," Bukavu has faced significant anthropogenic pressure, resulting in the loss of the characteristics that define a city. The city faces challenges such as poor sanitation (including metallic, organic waste, and sewage), inadequate water drainage systems, insufficient electricity supply, and a lack of socio-economic infrastructure such as public markets, playgrounds, and parking facilities. These issues contribute to uncontrolled urbanization [34]. Bukavu experiences a rapid population growth rate, similar to the rest of the African Great Lakes region. In 2016, the city had a population of ~ 876,000, with a projected growth rate of around 5%. It is estimated that the population will exceed 1.6 million by 2030 and 1.9 million by 2070 [34].

Figure 1 illustrates the boundaries of the municipalities and quarters within the Bukavu city. Among them, Kasha and Ibanda have a larger surface area compared to Bagira and Kadutu. Although Kasha is the largest in terms of size, it is the least densely populated in comparison with Ibanda and Kadutu. The figure also highlights the main locations where household waste is deposited or causing environmental pollution.

2.2 Methods

2.2.1 Household wastes characterization and quantification

To characterize the household wastes generated in the city, fieldworks were conducted during two periods: from December 2015 to February 2016 and from December 2016 to February 2017. The fieldworks involved conducting surveys at households. To ensure the validity and reliability of the results, we conducted our work over a period of three years from 2015 to 2017. During each period, waste quantification and characterization were carried out, followed by compost production, laboratory analysis, and greenhouse trials. Throughout all these stages, the same protocol was repeated. The surveys included questions about socio-economic information and waste management practices as suggested by Lunag and Elauria [35]. The information gathered included identifying the person(s) responsible for waste management in each household, determining the presence or absence of waste valorization methods and, if present, the specific methods employed. Additionally, households were asked to estimate the monthly quantity of waste generated, distinguishing between biodegradable and non-biodegradable waste. The total population and number of households in the city were already known [34], which aided in calculating the required number of households for the surveys. A sample size calculator available online (https://fr.surveymonkey.com/mp/sample-size-calculator/) was utilized, using the formula provided below. The formula incorporates *N* as the number of households, the population size, *e* as the error margin (in decimal percent), and *z* as the coefficient for a 95% confidence level (where z = 1.96).

$$N_{samples} = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + \left(\frac{z^2 \times p(1-p)}{e^2 N}\right)}$$

After performing the calculations, a total of 385 households were randomly selected for the surveys in the city. Waste samples were collected simultaneously to estimate the average quantity of waste generated per household. Specifically,

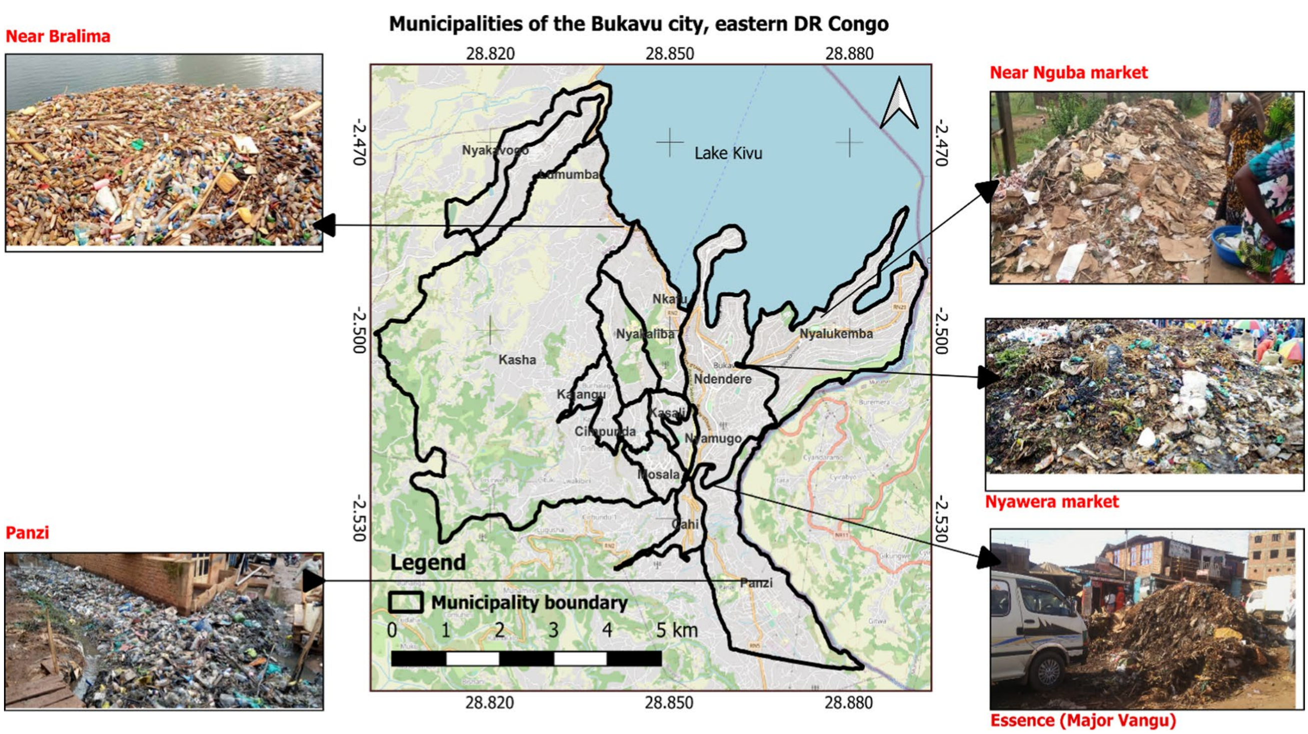

Fig. 1 The municipalities in the Bukavu city, eastern D.R. Congo. The figure shows also pictures of the main points where households and local markets deposit wastes

biodegradable waste samples were collected for the composting methods' trials. Plastic bags were provided to the households to facilitate the collection of these wastes. Additionally, a separate bag was given to collect non-biodegradable wastes such as bags, batteries, clothes, metal tools, plastics, and others. The collected wastes were then weighed using a HANNA-type scale. Due to limitations in time and financial resources, only biodegradable wastes from the Panzi and Nguba areas within the Ibanda municipality were selected for the surveys and composting methods.

2.2.2 Evaluation of the effectiveness of three composting methods used in this study

In this study, three local composting methods were evaluated: pile composting, ditch/pit composting, and vermicomposting. The objective was to identify the most effective and low-cost method that households could use to recycle their biodegradable wastes, with the aim of promoting its widespread adoption throughout the city. To facilitate the composting process, wooden decomposition boxes with dimensions of 1 m × 1 m × 1 m (1 m^3) were constructed. These boxes served to contain the waste materials while allowing for decomposition. For the pile composting method, plastic bags were used to cover the composting materials. In the case of vermicomposting, a specific type of worms called *Eisenia foetida* was utilized [36]. These worms were locally collected from various areas of the UEA Bukavu hill, particularly in its wet regions. *Eisenia foetida* belongs to the phylum *Annelidae*, class *Clitellata*, order *Oligochaeta*, family *Lumbricidae*, and genus *Eisenia*. A highly productive worm species thrives in temperatures ranging from 20 to 25 °C [37, 38].

The boxes used for vermicomposting were divided into three chambers. The first chamber served for waste reception, while the second chamber contained a mesh with small holes at the bottom to facilitate filtration and the movement of worms. The final chamber was well-constructed, and inside it, a permeable bag was placed to collect the leachate, which could be used as a liquid fertilizer.

A precomposting process was established. It helped in decomposition acceleration, reduction of odor and improved compost quality. It consisted of breaking down biological materials, with grinding (to obtain homogeneous mixture) and frequent turning.

During the monitoring of composting parameters, the decomposition of organic matter (OM) was evaluated based on two main parameters: temperature (°C) and pH. These parameters were measured on a weekly basis. A digital thermometer (HANNA brand) was used to measure the temperature, while a pH-meter (Mettler Toledo brand) was used to measure the pH of the composting materials.

At the end of the composting trials, samples were collected and analyzed following the protocols of the Laboratory of Soil and Water at UEA Bukavu. Additional samples were taken to the Molecular Biology Lab of the same institution for phytotoxicity assessment. Phytotoxicity refers to the ability of composts to produce substances that can inhibit plant growth [38]. In this study, the germination rate and germination index were used as indicators to assess the phytotoxicity of the produced composts.

To evaluate the germination index (GI), 100 seeds of common bean (*Phaseolus vulgaris* L) and soybean (*Glycine max* L.) were placed on a Petri dish with three replications. The seeds were mixed with 5 g of compost and deposited on a tissue paper, and 20 ml of distilled water was added. The germination index (GI %) was determined by measuring the average root length and the average number of germinated seeds in each sample, and comparing them to a control treatment. The relative seed germination (RSG %) and relative root elongation (RRE %) were calculated using the formulas proposed by literature [39, 40]:

$$RSG(\%) = (NSGC/NSC) \times 100$$

$$RRE(\%) = (MREGC/MREC) \times 100$$

$$GI = (RSG \times RRE)/100$$

where: NSGC: Number of seed germinated in the compost extract, NSC: Number of seeds in the control Petri dish, RSG: Root mean elongation in the compost extract, RRE: Root mean elongation in the control

This trial helped us evaluate the compost's ability to inhibit seed germination due to the presence of phytotoxic substances. The seeds used in the experiment were obtained from the National Seed Service (SENASEM) to ensure their high germination capacity.

2.2.3 Parameters used to evaluate the three composting methods

As mentioned earlier, three types of compost products were obtained during the composting process, and samples were taken on a weekly basis to monitor the decomposition progress. The analysis of these samples involved determining the physical and chemical properties of the composts being produced. Two key parameters considered in the analysis were pH and temperature (T °C).

After four months of the decomposition process, compost samples were collected and analyzed in the laboratory. The focus of the analysis was primarily on nutrient content, including Olsen extractable phosphorus (P), total carbon (C) and nitrogen (N), as well as calcium (Ca) and magnesium (Mg). These nutrients play a crucial role in determining the quality and fertility of the compost, as they contribute to the nutrient availability for plant growth and soil health. Analyzing these parameters helps in evaluating the effectiveness of the composting methods and their potential as organic fertilizers for agricultural purposes.

2.3 Evaluation of the effect of composts produced on growth and productivity of common bean and soybean under greenhouse conditions

In order to assess the impact of the three compost types on the growth and development of common bean and soybean, experimental trials were conducted in a greenhouse environment. The greenhouse was set up at the Faculty of Agriculture and Environmental Sciences of UEA Bukavu. The temperature data collected both inside and outside the greenhouse over the course of four months (from April to July) are provided in the Supplementary material (Table S1). Additionally, Table 1 presents the analysis of soil samples that were used in the pots for the experiment.

The trials followed a Completely Randomized Design (CRD) with four replications. Pots with a capacity of 5 L were utilized as experimental units, and two seeds were sown in each pot. Four treatments were implemented, which included the three types of compost and one control treatment. Each treatment consisted of 12 pots, resulting in a total of 48 pots for each crop. The pots were arranged in the greenhouse on a surface area measuring 5 m × 3.6 m. A distance of 0.25 m was maintained between two adjacent plots, while a spacing of 0.5 m was maintained between replications.

The pots were filled halfway with soil obtained from the farm of the aforementioned faculty. The characteristics of the soil samples used in the experiment are provided in Table 1. Analysis of the soil samples conducted over a two-year period revealed that the soil was strongly acidic, with a pH range of 5.1–5.5 according to the USDA classification. The soil also exhibited low organic matter content (< 5%) and a very low cation exchange capacity (CEC) of 12.48 and 16.1 Cmol kg^{-1} for the first and second year, respectively. Furthermore, the soil is clayey in nature, specifically of the kaolinite type, and exhibited low nutrient content.

The seeds were planted on April 10, 2016, and the harvest took place on July 6, 2016. To meet the water requirements of the crops, watering was carried out by pouring half a liter of water into each pot every two days. After the

Table 1 Characteristics of soil used as substrate in the greenhouse during the two year trials

Parameters	Started period (2015)	Ending period (2017)
pH-H_20	5.41	5.44
pH-KCl	3.90	3.90
Carbon (C, %)	1.42	1.53
Organic matter (OM, %)	2.44	2.63
%Total Nitrogen (TN, %)	1.92	1.98
Ca^{2+} (Cmol kg^{-1})	7.45	5.31
Mg^{2+} (Cmol kg^{-1})	1.82	1.09
K^{+} (Cmol kg^{-1})	0.94	0.43
CEC (Cmol kg^{-1})	12.48	16.10
P_{ppm}	13.45	11.82
Sand (%)	22	24
Clay (%)	64	63
Silt (%)	14	13

flowering stage, the watering quantity was reduced by half and eventually stopped during the maturity stage. The compost application was done 10 days prior to planting by creating a circular mound around the plants, which was then covered with soil to prevent nutrient loss through volatilization. The vermicompost was divided into two types: solid compost and leachate. The leachate was applied at a rate of six liters per treatment, with half a liter per pot.

Two crops, common bean and soybean, were used in the experiment. The seeds used were obtained from the CIAT HarvestPlus Project, and their characteristics are described in Table 2.

To evaluate the growth and productivity of the crops, various parameters were measured. These included the seedling emergence rate (%) and germination index (GI %). Plant height, number of leaves, and root length were recorded at the fifteenth, thirtieth, fortieth, and sixtieth day after sowing (DAS). The number of leaves was specifically considered as a productivity factor for common bean because in Bukavu and the eastern DRC region, common bean leaves are commonly used as a vegetable [41].

Productivity parameters such as the number of pods per plant, number of seeds per pod, hundred-seed weight, total biomass, and harvest index were also collected. The harvest index was calculated as the ratio of the number of grains per plant to the total plant biomass, expressed as a percentage. Additionally, two nodulation parameters related to nitrogen fixation through nodule formation were considered: (a) the number of nodules per plant and (b) the number of nodules on the main root. These data were manually collected by counting.

2.4 Data treatment and statistical analysis

Data analysis was conducted using various statistical methods. Descriptive statistics such as mean, standard deviation, and frequencies were calculated for quantitative and qualitative data obtained from household surveys. For the experimental trial data, analysis of variance (ANOVA) was performed using a Completely Randomized Design (CRD) to determine significant differences among treatments. When significant differences were observed, post-hoc tests, specifically the Least Significant Differences (LSD) test at a 5% significance level, were used to separate the means. The statistical software R Studio and R 4.0.1 [42] were utilized for data analysis. The "*ggplot2*" package in R and Microsoft Excel 2018 were employed for graphical representation. It is noteworthy that certain parameters, such as the number of leaves, number of pods per plant, and number of grains per pod, were found to have a non-normal distribution. Therefore, the Kruskal–Wallis and Friedman tests, which are non-parametric statistical tests, were employed to analyze these parameters at a 5% significance level [43].

Table 2 Characteristics of biofortified variety of common bean (*Phaseolus vulgaris* L.) and soybean (*Glycine max* L.) used as test crop during the greenhouse trials

Varieties	CODMLB001	PK06
Origin	INERA/Mulungu	PNL-INERA/Mulungu
Growth habit	Bush	–
Owner	INERA/Mulungu	INERA/Mulungu
Time to flowering (days)	41	38
Time to maturiy (days)	85	95–105
Weight of 100 grains (g)	32.4	16.2
Yield in greenhouse (kg ha^{-1})	1502.5	2000
Elevation (m.a.s.l)	~1650	1000–2100
pH	5.5–7.8	5.5–7.8
Rainfall (pmm)	–	–
Fe (mg/g)	81	–
Zn (mg/g)	34	–
Grain colour	Red mottled	Curry
Seed size	Medium	Medium

3 Results

3.1 Characterization of wastes produced by Bukavu households

The results from the field survey conducted in Bukavu city revealed that only ~ 5% of the wastes produced by households (in terms of weight) were biodegradable. These biodegradable wastes primarily consist of food waste, particularly vegetable leftovers (such as cabbage, herb leaves, and amaranths), cassava and maize bread residues (locally known as "foufou"), potato leaves, and banana blooms. The estimated monthly production of biodegradable waste per household ranged from 250 to 490 kg.

Regarding waste management, children were primarily responsible (82%) for activities such as waste storage, removal, or incineration within households. In a significant number of households, women (15%) were involved in waste management. Some local organizations and associations in the city center (3%) have shown an interest in waste management and treatment. Figure 2 illustrates the frequencies of waste types (a), the individuals involved in waste management (b), and the methods used for waste management in Bukavu. Urban agriculture plays a crucial role in Bukavu, with predominantly subsistence farming practices, mainly carried out by women (80%) for the survival of their families. Common crops cultivated include vegetables (including some cassava and corn) and legumes such as beans and peas. The peri-urban agglomerations of Bagira, Nguba, and Panzi were identified as areas where urban agriculture is frequently practiced. Livestock farming is relatively limited due to land scarcity, but mini-livestock rearing, which includes raising pigeons, chickens, rabbits, and other small animals, is present. However, households expressed concerns that urban farming and livestock activities contribute to the decline and degradation of Bukavu.

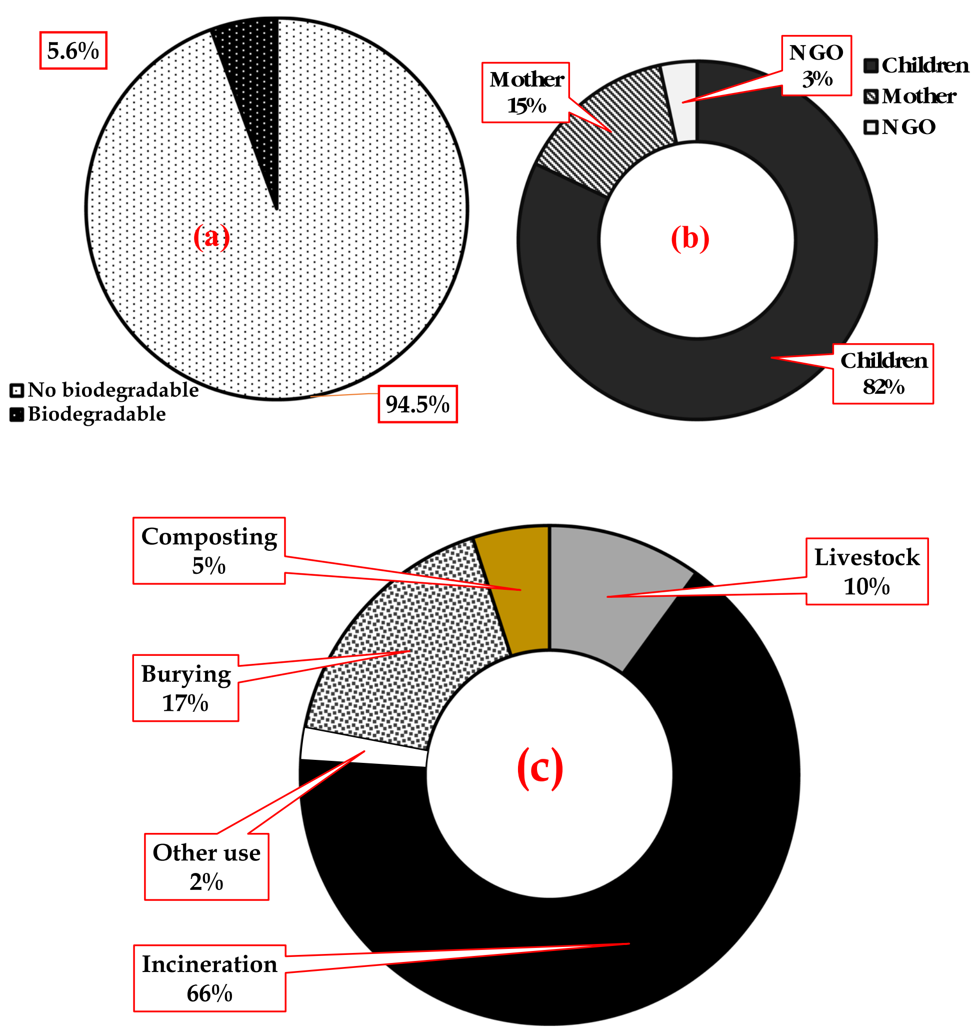

Fig. 2 Domestic waste types (**a**), waste managers (**b**) and waste management methods (**c**) by households in Bukavu, South-Kivu province

Among the various methods used for waste management and valorization, the survey identified five primary methods employed by households in Bukavu. These methods include composting (5%), burying (17%), using waste as livestock feed (10%), and incineration (66%). Only a small percentage of households (~ 2%) reported using alternative methods such as producing plastic floor tiles or using local plastic bags for waste management (Figs. 2, 3). It was observed that there are no designated storage locations for waste, resulting in waste being deposited on crossroads or outside households' parcels. This lack of proper waste management infrastructure poses a threat to human health and contributes to unhealthy conditions, particularly in the deposit sites, across all municipalities of the city. Biodegradable waste, mainly composed of vegetable leaves, lawn clippings, and tree leaves from gardens, is often used as livestock feed, primarily for goats or pigs. Some households reported practicing composting methods, with three main approaches being utilized: ditches, piles, and vermicomposting (Fig. 4).

Quantitative data revealed the productivity and compost yield obtained from each composting method aforementioned. With one ton of biodegradable waste, vermicomposting resulted in ~ 290 kg of solid compost, representing a productivity rate of ~ 30%. The pile method yielded 330 kg of compost (~ 32% productivity), while the ditch method demonstrated the highest productivity, with 400 kg of compost (~ 38%). Moreover, ~ 70 L of nutrient-rich leachate were collected from vermicomposting in addition to the solid compost obtained (Fig. 4b).

Fig. 3 Some images of waste and dumping sites in the Bukavu city (waste from bags and household remains in Nguba (**a**) and Muhungu (**b**), a wooded area polluted by waste and considered as a dumping site in the municipality of Ibanda (**c**), waste found along the shores of Lake Kivu, degrading the lake's banks (**e** and **f**). Diagram of images of sites polluted by household waste (e) (*most of pictures were obtained from: Muderhwa Bienvenu*)

Fig. 3 (continued)

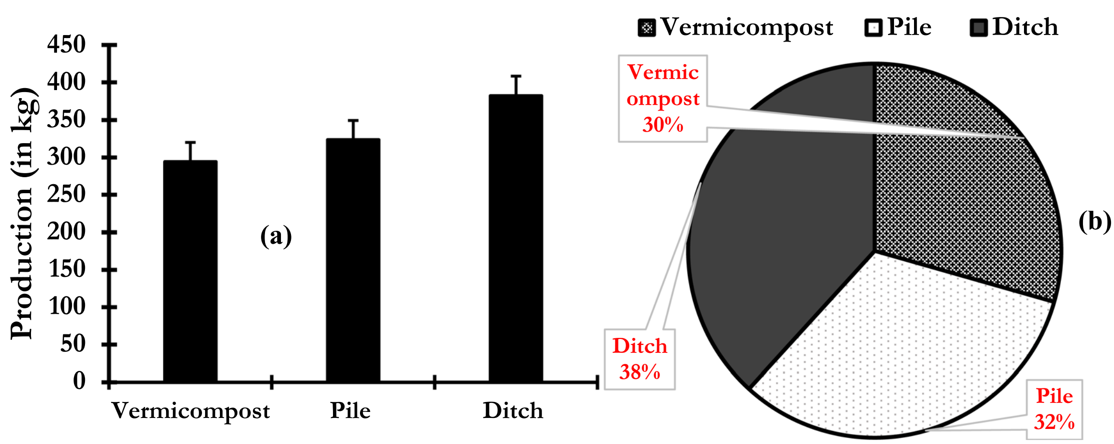

Fig. 4 Quantity of compost produced by each composting methods using a ton of biodegradable wastes (**a**) and productivity of each method (**b**) in Bukavu city

3.2 Effects of three composting methods on physicochemical proprieties of compost

3.2.1 Temperature and pH

When comparing the three composting methods used for biodegradable waste in Bukavu, the temperature and pH evolution patterns indicated a progressive increase followed by reaching a peak at around the third week, after which they begin to decrease and stabilize by the seventh week. Both the temperature and pH graphs exhibited a "bell" shape, and indicating the dynamic nature of the decomposition process.

In terms of temperature (in °C), the compost from the pile method initially reached ~ 20 °C in the first week and increased to around 26.2 °C in the following week. The highest temperature was observed after three weeks, reaching ~ 35.8 °C, indicating high microbial activity. From the fourth week onwards, the temperature started to decrease and remained relatively stable until the end of the trial, indicating the completion of decomposition and compost maturity. In contrast, the lombricomposting method and the ditch composting method showed the lowest temperature values throughout the experiment, with the temperature of these three composts eventually stabilized at around the same value of ~ 22.5 °C (Fig. 5a).

Similarly to the temperature trend, the pH graph exhibited a similar pattern (Fig. 5b). The initial pH values of the composts were around 6.1 in the first week, which increased to approximately 7.2 in the third week, and reached their peak in the fifth week (9.4 for vermicomposting, 9.0 for pile composting, and 8.5 for ditch composting). From the sixth week onwards, the pH values of all the composts started to decrease and stabilized at around 7.5 to 8.0. Pile composting showed the lowest pH from the beginning of the trial until the fourth week, whereas ditch composting exhibited the lowest pH values from the fifth week until the end of the trial. Lombricomposting consistently maintained higher pH values throughout the experiment.

3.3 Effect of the four composts obtained from the composting methods on nutrients availability.

The results obtained over the course of two years did not show any significant differences, but variations were observed between the different composting methods. Lombricompost exhibited higher pH values (8.11 and 7.44) compared to the other methods. It also showed higher levels of phosphorus (950 and 961 ppm), nitrogen, and calcium. On the other hand, ditch composting yielded products with lower values in these parameters (Table 3). The germination index (GI) varied significantly among the different composts ($p < 0.05$). The leachate obtained from lombricompost showed high GI values (90% and 95%), followed by solid lombricompost (88% and 90%). Pile compost exhibited the lowest GI value (70%). All the composts had a rich organic matter content, ranging from 11.7% to 14.9%, with the highest values observed for lombricompost and ditch compost. The results also indicated that the leachate produced had a lower organic matter content but higher levels of nutrients such as total nitrogen (TN), total phosphorus (TP), and cations such as calcium (Ca) and magnesium (Mg) (Table 3).

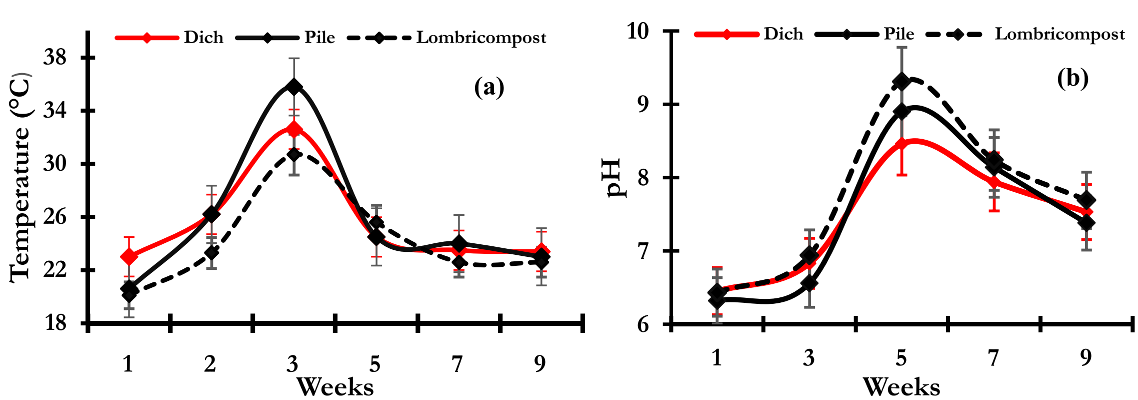

Fig. 5 Evolution of compost temperature (**a**) and pH (**b**) during the decomposition time of nine weeks

Table 3 Nutrient composition of composts obtained using different methods on domestic wastes from Bukavu municipalities

Nutrients										
Compost types	pH_{eau}	pH_{KCl}	TP	TN	C	Ca	Mg	OM	C/N	GI
1st year	–	–	mg kg^{-1}	%	%	meq/100 g		%	–	%
Pit/Ditch	6.98	6.25	893	0.498	7.891	3.83	1.75	13.572	15.909	80
Pile	7.57	7.00	859	0.468	6.945	2.78	2.56	11.945	14.839	70
Leachate	8.11	7.24	961	0.897	6.821	3.82	2.91	11.732	7.604	90
Vermicompost	8.97	7.6	870	0.688	8.833	3.12	1.25	15.170	12.860	88
Means	7.9	7.15	895	0.638	7.622	3.38	2.12	13.105	12.803	83.3
Second year										
Pit/Ditch	6.75	6.65	900	0.489	7.92	3.22	1.60	13.588	16.155	85
Pile	7.72	7.23	850	0.457	6.96	2.62	2.40	11.868	15.098	70
Leachate	7.44	6.96	950	0.875	6.72	3.24	2.82	11.524	7.657	95
Vermicompost	7.16	6.89	860	0.672	8.71	2.61	1.21	14.964	12.946	90
Means	7.24	7.01	890	0.62	7.55	2.93	2.02	12.986	12.964	80

Pt Total phosphorous, *Nt* Total nitrogen, *C* carbon, *Ca* Calcium, *Mg* Magnesium, *OM* organic matter, *C/N* ratio carbon to nitrogen, *GI* germination index

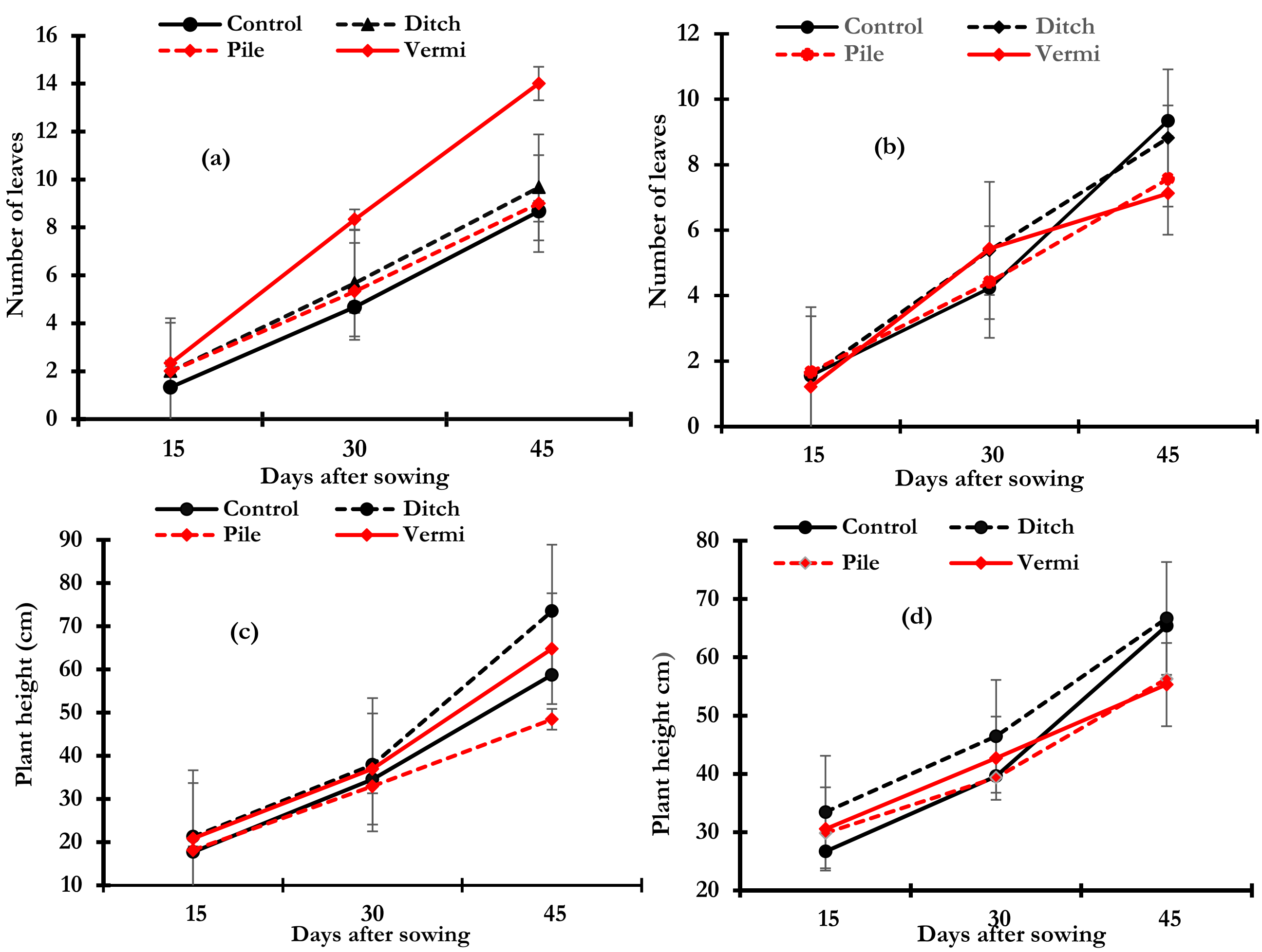

Fig. 6 Variation of the number of leaves and plant height for common bean (**a**, **c**) and soybean (**b**, **d**) according to compost types in greenhouse conditions

3.4 Effect of compost manure types on common bean and soybean growth and yield components

3.4.1 Effect compost on plant growth parameters

Figure 6 shows the evolution of the number of leaves per plant for common bean (a) and soybean (b) under greenhouse conditions. (i) For common bean, plants grown in lombricompost pots exhibited a higher number of leaves throughout the trial. At the 15th day after sowing (DAS), all compost types had 2 leaves, but by the 30th DAS, plants in lombricompost pots reached 8 leaves, while the others remained at 4–6 leaves. At the beginning of the maturity stage, plants in the pile compost pots had 14 leaves, while ditch and lombricompost pots had 8–10 leaves. The control plot had the lowest number of leaves, although not significantly different from the pile and ditch compost pots. (ii) For soybean, a similar trend was observed. The ditch and control pots had the highest number of leaves, ranging from 8–11 leaves. There was no significant difference between the ditch and control pots, as well as between the lombricompost and pile pots. Therefore, based on the number of leaves, it can be concluded that common bean responded well to the applied compost, while soybean showed a similar response regardless of the compost type. The results for plant height (in cm) also showed significant differences between the compost types. Ditch and lombricompost pots resulted in taller plants, with heights of 40 cm at the 30th DAS and 75 cm at the 45th DAS for common bean, and 45 cm at the 30th DAS and 68 cm at the 45th DAS for soybean. Between the two crops, ditch compost consistently promoted taller plants. For soybean, there was no significant difference between the pile and lombricompost pots in terms of plant height.

3.4.2 Effect off applied compost types on nodulation capacity of common bean and soybean

The effect of compost application on the nodulation capacity was evaluated using two parameters: the total number of nodules per plant and the number of active nodules. According to Fig. 7, both the total number of nodules and the number of active nodules varied significantly with crops ($p < 0.05$) and compost types ($p < 0.05$). For soybean, there was no significant effect of compost types on the total number of nodules, with an average of ~ 14 nodules per plant observed across all compost types. However, for common bean, significant differences were observed. Plants grown in lombricompost had an average of 6.5 nodules per plant, while plants in pile and control pots had 5 and 4 nodules, respectively (Fig. 7).

Regarding the number of active nodules, for soybean, pile and ditch composts showed higher values (12 active nodules), followed by vermicompost (lombricompost), while control plants had only 8 active nodules. For common bean, plants from vermicompost had the highest number of active nodules (5.8), followed by ditch and pile composts (4–5), and the control plants had 3.5 active nodules. These results indicate that compost type influenced the nodulation capacity, particularly in common bean, where lombricompost showed a positive effect on both the total

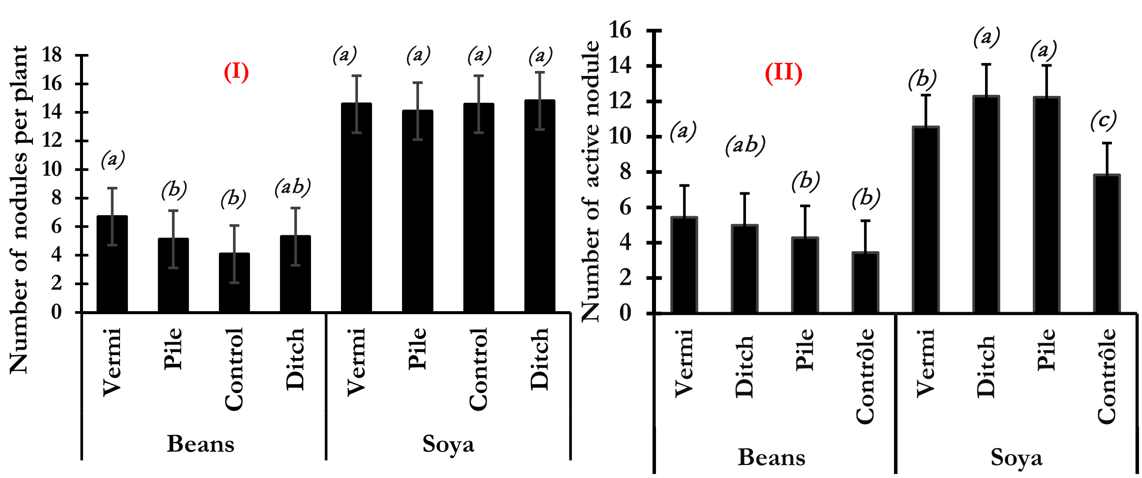

Fig. 7 Variation in total number of nodules per plant (I) and number of active nodules per plant for common bean and soybean grown on different compost types (*active nodule are identified in doing section in nodule and color appreciation was made: if a red color is observed inside the nodule, that means the nodule is active, if not, then the nodule is inactive*)

Table 4 Effect of compost types on yield parameters of common bean and soybean grown in greenhouse conditions

Crops	Types	Root length (cm)	Weight of 100 grains (g)	Number of grains per pod	Number of pods per plant
Common beans	Control	24.6 ± 0.1a	37.1 ± 6.9b	4.3 ± 2.3c	3.0 ± 0.5a
	Ditch	19.2 ± 0.7c	41.5 ± 5.3a	5.0 ± 1.9c	3.4 ± 0.5a
	Pile	20.6 ± 0.8b	37.6 ± 1.5b	3.5 ± 0.8c	3.0 ± 0.1a
	Vermicompost	17.1 ± 1.6c	44.2 ± 3.5a	5.4 ± 1.1c	3.4 ± 0.5a
Mean (Common bean)		***20.4 ± 3.0***	***40.1 ± 4.8***	***4.5 ± 1.5***	***3.2 ± 0.4***
Soybean	Control	18.3 ± 5.5c	12.9 ± 2.5c	12.2 ± 4.8a	2.8 ± 0.9a
	Ditch	21.4 ± 5.9ab	13.7 ± 1.4c	12.3 ± 4.1a	3.1 ± 0.7a
	Pile	20.3 ± 6.7b	12.9 ± 0.7c	7.8 ± 4.5b	2.8 ± 0.7a
	Vermicompost	17.2 ± 4.9c	13.2 ± 1.9c	10.6 ± 0.6ab	2.7 ± 0.6a
Mean (Soybean)		***19.3 ± 5.2***	***13.2 ± 1.5***	***10.7 ± 0.7***	***2.9 ± 0.6***
	Mean	**19.7** ± 4.4	**24.0** ± 13.9	**8.3** ± 1.9	**3.0** ± 0.7
	C.V.%	**9.1**	**7.1**	**13.3**	**8.4**
	P-value	*< 0.001***	*< 0.001***	*0.014**	*0.454 ns*
	Tukey HSD	3.6	5.4	2.1	0.9

number of nodules and the number of active nodules. In soybean, the effect of compost type was not significant for the total number of nodules, but pile and ditch composts promoted a higher number of active nodules compared to the control.

3.4.3 Effect of compost types on yield parameters of common bean and soybean

From the analysis conducted, it was observed that the root length, weight of hundred grains, and the number of grains per pod varied with crops and compost types (Table 4). For common bean, plants in the control plot had the longest root length (24.6 cm), followed by the pile compost (20.6 cm), ditch compost (19.2 cm), and vermicompost (17.1 cm). In the case of soybean, the ditch compost (21.4 cm) and pile compost (20.3 cm) resulted in higher root lengths. In terms of weight of hundred grains, vermicompost produced common bean plants with the highest weight (44.2 g), followed by the ditch compost (41.5 g), and the control treatment (37.1 g). Similar trends were observed for the number of grains per pod, with vermicompost (5.4 grains), ditch compost (5.0 grains), and control treatment (4.3 grains) resulting in different values.

The number of pods per plant did not show a significant difference among the compost types. For soybean, the same trend was observed. Vermicompost led to plants with the highest weight of hundred grains (13.2 g), followed by the ditch compost (13.7 g), and the pile compost (12.9 g). The control treatment resulted in plants with a weight of hundred grains of 12.9 g. The number of grains per pod followed a similar pattern, with vermicompost (5.0 grains), ditch compost (5.0 grains), pile compost (4.8 grains), and the control treatment (4.6 grains). These results indicate that compost type influenced the root length, weight of hundred grains, and the number of grains per pod in both common bean and soybean. Vermicompost generally showed positive effects on these parameters, resulting in higher values compared to the other compost types. According to the analysis of plant biomass and harvest index (HI), significant variations were observed between different compost types and different crops. Common bean plants generally had higher plant biomass and harvest index compared to soybean plants. For common bean, there were no significant differences in plant biomass among the three compost types (142 g), but all compost-treated plants showed significantly higher biomass compared to the control treatment (98 g). However, vermicompost showed higher variability in plant biomass (Fig. 8).

For soybean, the ditch compost (88 g) and vermicompost (86 g) resulted in higher plant biomass compared to the pile compost (77 g) and control treatment (82 g). Regarding the harvest index (HI), vermicompost-treated pots showed higher HI values for both common bean (43%) and soybean (15%) compared to other compost types. The ditch compost had a HI of 36% for common bean and 13% for soybean. The pile compost and control treatment had similar HI values, with 30% for common bean and 12% for soybean. These results indicate that the type of compost used significantly influenced plant biomass and harvest index for both common bean and soybean. Vermicompost generally resulted in higher values for both parameters, indicating its positive impact on crop productivity (Fig. 8).

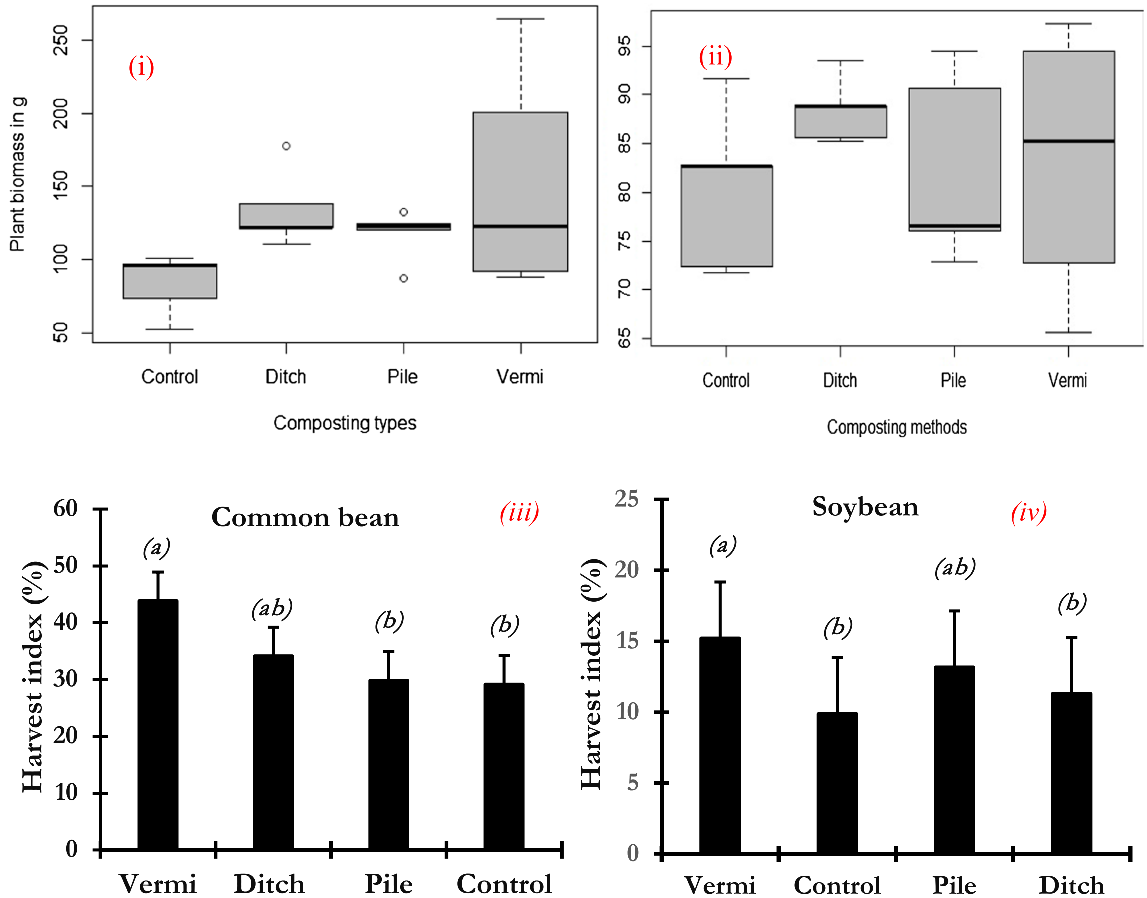

Fig. 8 Variation of the plant biomass (i: for common bean, and ii: soybean), and harvest index (HI) (iii: common bean and iv: soybean) depending on the types of compost. Treatments with same letters are not significantly different at 5% p-value threshold. **: < 0.001, *: < 0.05, ns: non-significant. C.V.: coefficient of variation

4 Discussion

4.1 Composting as an alternative for recycling the biodegradable waste that pollutes the city of Bukavu

The study emphasizes the importance of valorizing household wastes through various simple and less expensive methods, which would not only enable waste management but also reduce the increasing dependence of farmers on costly chemical fertilizers. By sorting and treating the waste through composting, which is a cost-effective approach, the waste that was once a source of pollution and a threat to public health can be transformed into a resource that improves the physical and chemical properties of the soil, providing nutrients and increasing crop yields [44]. This approach can be implemented at various scales, from individual households to neighborhoods or even to the entire city. However, efficient municipal solid waste management systems require professional management, informed public participation, and appropriate legislation and policies [45].

It is important to note that this study focused only on biodegradable wastes and did not include non-degradable materials such as metals and plastics. While these non-degradable wastes constitute a significant portion (94.5%), future research should focus on recycling and valorizing these types of wastes. Efforts are being made in the city to utilize these wastes, such as producing charcoal for combustion and manufacturing small slabs for infrastructure. Municipalities in low- and middle-income countries often allocate a significant portion of their budgets to sewage services, despite a significant portion of solid waste remaining uncollected [46, 47].

The biodegradable waste is composted for use in urban agriculture. It is important to assess the monitoring parameters of quality. Throughout the study, the pH and temperature (°C) were monitored as key variables during the decomposition process. These variables follow a well-known trend in organic matter decomposition, particularly the mesophilic and thermophilic phases [48]. During the mesophilic phase, the temperature gradually increases due to the metabolic activity of mesophilic microorganisms, reaching around 40–45 °C within a few days. This phase is characterized by a decrease in pH due to the production of organic acids. The pH increase during decomposition enhances organic matter degradation and decreases the carbon-to-nitrogen (C/N) ratio. In the final week of the process, the pH decreases, reaching a neutral level, indicating the depletion of organic matter and nitrification reactions [35, 40, 48, 49]. The thermophilic phase, also known as the remediation phase, occurs at temperatures above 45 °C. Thermophilic microorganisms replace the mesophilic ones and decompose complex carbon sources like cellulose and lignin. During this phase, ammonia is converted to nitrogen, leading to an alkaline pH in the mixture [48, 49].

4.1.1 Household wastes composting as a useful tool in urban agriculture

Bukavu is a place characterized by low food production (through urban agriculture) but high consumption levels [50, 51], leading to a reliance on products from outside the country and rural areas of South-Kivu. The economy of Bukavu, like many other African cities, is predominantly low-income and based on various activities classified into three levels: production, processing, and public and private services provided to households and businesses. In South-Kivu, where over half of households face food insecurity [51–53], men, women, and children engage in diverse agricultural activities such as vegetable production, horticulture, fishery (in the Lake Kivu), mini-livestock, tree plantation, and mushroom cultivation. The finding that children are primarily responsible (82%) for waste-related activities within households in eastern DRC raised significant concerns regarding child labor, health, and environmental hazards [11, 12, 35]. Several factors contribute to this situation, including socio-economic conditions, cultural norms, and inadequate waste management infrastructure. Firstly, socio-economic factors play a crucial role in children's involvement in waste management activities. In very few households, families rely on informal waste collection and recycling as a source of income. Children are often engaged in these activities to supplement family income or contribute to household chores, as poverty remains widespread in the country [35]. Secondly, cultural norms and gender roles also influence children's involvement in waste management tasks. Traditional gender stereotypes may assign domestic responsibilities, including waste management, to girls at a young age, perpetuating inequalities and limiting their access to education and opportunities for personal development. Furthermore, inadequate waste management infrastructure exacerbates the burden on children. Limited access to formal waste collection services and recycling facilities means that households often resort to burning or burying waste in informal dumpsites, exposing children to health risks from air pollution and toxic emissions [11, 12]. Addressing the issue of child involvement in waste management requires a multi-faceted approach, and need for policies and interventions to promote education and child protection to prevent children for hazardous labor practices. This includes measures to improve access to quality education, raise awareness of child rights, and enforce legislation against child labor. Those efforts can be also focused on improving waste management infrastructure and promoting sustainable waste practices. Investing in formal waste collection systems, recycling facilities, and community-based initiatives can reduce reliance on child labor and mitigate environmental pollution.

Urban and rural agriculture has become a significant source of employment and income for many young urban residents. Unfortunately, urban overexploitation and land scarcity are generally ledding to unproductive soil (with very poor soil fertility). To increase productivity, farmers rely on various fertilizers. On one hand, there is a need to intensify agricultural lands to increase productivity, while on the other hand, enormous amounts of household waste go untreated. This study establishes a connection between agriculture and household waste. According to Lee-Smith [23], the success of this relationship depends on waste and effluent treatment methods that produce usable agricultural products with minimal risk to human health and the environment. Composting is presented as a sustainable method to fill this gap, with vermicomposting or ditch composting being advisable at various scales, from individual households to the entire city [54–56]. Implementing an efficient system for collecting household waste from neighborhoods and transporting it to disposal facilities would significantly improve waste management and promote recycling and recovery activities, thus advancing urban and rural agriculture [23].

The results of the study demonstrated a significant difference between pots fertilized with compost and the control pots in terms of crop productivity and growth, particularly for common beans and soybeans. This improvement can be attributed to several factors. Firstly, the compost used in the study was rich in nutrients such as phosphorus, nitrogen, calcium, and magnesium [57–59], which are beneficial for plant growth. Additionally, the compost had a high germination index (meaning no phytotoxic substances were available), as found by other researchers. Compost increases the availability of nutrients to plant roots and improves soil structure and stability. Tropical soils, which are often degraded, lack adequate nutrient retention and absorption capacities. Compost, with its high organic matter concentration, could have facilitated water retention, enhanced soil physical properties, and promoted crop production. Numerous studies worldwide have demonstrated the positive effects of vermicomposts on biological activity, germination, seedling development, and yields of various greenhouse crops [35, 58, 59, 61–63]. The growth and yield of some crops, including soybeans [60], tomatoes, maize, and common beans, have been shown to be enhanced by the addition of vermicomposts to soils. In the case of this study, vermicompost improved the growth and productivity of common beans and soybeans in greenhouse conditions on tropical degraded soil of South-Kivu.

Although differences were observed between the compost-treated pots and the control, the effect remains relatively modest. Scaling up such an approach would require considering a combination of compost and mineral fertilizers, as the composts produced were poor in the essential plant nutrients (mainly N, P, and K) required for major crops [64, 65]. The Integrated Soil Fertility Management (ISFM) approach proposes integrating micro-doses of mineral fertilizers and organic manure to meet crop nutrient requirements and improve yields [63, 66, 67]. For peri-urban, rural, or urban agriculture, the challenge lies in optimizing the combination of limited-quality fertilizers and expensive mineral fertilizers to support intensive agriculture and promote the utilization of locally available natural materials [56, 68].

While the application of composts significantly improves the growth and productivity of common beans and soybeans in greenhouse conditions, further studies are warranted to explore their influence on acidic soils and identify more efficient and profitable utilization methods, including on-farm trials. It is also important to quantify the contribution of exogenous microorganisms introduced by the composts and the indigenous microorganisms present in the soil. Additional research should focus on other parameters of soil biological activity, the impact of different population densities of arthropods and earthworm species, and the effect of earthworm population density on waste decomposition rates. The volume of waste also plays a role in the speed and quality of waste decomposition, with larger volumes potentially affecting the process.

5 Conclusion

This study focused on optimizing composting methods for household organic waste to enhance nutrient availability and improve the growth and yield of leguminous crops in urban agriculture in Bukavu. The findings indicated that while the per-household output of organic waste was low, the cumulative amount generated by the entire city was substantial. Proper waste management was crucial to alleviate the burden on the population and reduce pollution in the aquatic ecosystem. Composting proved to be a suitable local solution for valorizing these wastes, with vermicomposting being the most effective among the tested techniques. It positively influenced the growth and yield parameters of common beans and soybeans. However, its application is currently limited to a small number of households and it is challenging to implement at a large scale, such as for recycling the entire city's waste. Therefore, alternatives such as ditch or pile composting methods can be considered, even though the resulting composts may have different chemical properties compared to the vermicompost.

While composting presents opportunities for organic waste recovery, there are still significant challenges to overcome, particularly when it comes to large-scale implementation. The management of other waste types, such as plastics and metals, also remains a significant challenge that requires the development of alternative solutions. Increasing awareness and promoting waste collection among the populations and local decision-makers are essential for addressing these challenges. Strengthening the existing taxation system, ensuring proper monitoring, and equipping waste collection agents are important steps. This study highlights the potential value of organic waste in compost production for urban agriculture, offering an agro-ecological approach as an alternative to chemical fertilizers. Urban waste composting contributes significantly to achieving Sustainable Development Goals (SDGs) by mitigating environmental impacts, promoting sustainable consumption, and generating economic opportunities. By diverting organic waste from landfills and returning nutrients to the soil, composting reduces greenhouse gas (GHG) emissions, soil pollution, and chemical fertilizer use. Additionally, composting can create income-generating activities, in eastern DRC communities, while fostering community resilience and social inclusion through participatory waste management initiatives.

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Author contributions CBG: Drafting, review, analysis, fieldworks, AM,ABN, EBM: editing, review and calculation, MMJ and MNG coordination and supervision

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Data availability Data from this paper will be available on reasonable request from the main author.

Declarations

Ethics approval The study protocol was approved by the Interdisciplinary Center for Ethic Research CIRE of the Université Evangélique en Afrique (UEA), Ref: CIRE 008/DPSK/118PP/2022. We obtained consent from all resource-persons and households for data collection after ensuring the participants of the confidentiality in use of data collected.

Consent to participate The authors agree the position and consent the publication of this paper. Informed consents were obtained also from all participant authors.

Consent for publication All the participant and households interviewed consented to participate and agree the publication of the results; informed consents were obtained from all participants.

Plant reproducibility The plant used in this study were obtained from the INERA GeneBank. All the national guidelines and legislation from MULUNGU Station of INERA-DRC were followed. We also certify that the varieties (soybean and common bean) used are not on the IUCN red list index of threatened species Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Competing interests The authors confirm that there is no competing of interests in publishing this paper.

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