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ORIGINAL RESEARCH

Comparison of the evolution of physicochemical and microbial characteristics of the wastes, those most commonly generated in Algeria during composting

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Abstract

Purpose This paper focuses on monitoring the behavior of five different types of waste and humus during composting to see the impact of the nature of the substrate on the process and the quality of mature compost.

Method Green waste, coffee waste, household waste (Fraction of the household waste which having dimensions smaller than 8 mm) and humus were collected separately from different areas of Oran city, western Algeria, composted in windrows of 2 m long, 1 m wide, and 0.5 m high each for 150 days during the winter and spring period (2019-2020). The physicochemical parameters and characteristics were determined on the one hand, and on the other hand, the evolution of the microflora was monitored.

Results The results show a correlation between the parameters of each substrate. Furthermore, it was found that green waste, coffee waste, and household waste can give the best quality of compost if the process conditions are respected (maintenance of C/N ratio and moisture level). However, small waste and very small waste can also be used to amend green areas and public gardens. The results also showed that the concentration of pathogenic microorganisms such as Salmonella and Shigella did not exceed the NFU44-051 standard.

Conclusion The findings support the industrialization of waste valorization by composting as an effective technique for waste reduction given the current situation and encourage investors and promote the industrialization of waste recovery by composting in Algeria.

Keywords Composting, Valorization, Wastes, Biodegradation, Bio-fertilizer

Introduction

In the 18th century, Lavoisier said that "nothing is lost, nothing is created, and everything is transformed". At the dawn of the 21st century, no one could dispute this statement. While waste has long been considered worthless residue, today's industrial production, consumer activities, and consumers recognize that waste treatment is the ecological challenge of the end of this century. Thus, implementing a real economic sector for waste treatment is indispensable (Scriban and Arnaud 1993). With the demographic evolution and the growing urbanization in developing countries, the quantity of urban waste produced is constantly increasing, which is of great concern to local authorities and inhabitants, who are very much aware of the associated risks. Several composting initiatives have been carried out in cities in developing countries because it is an interesting way of treating the organic fraction of household waste. It also allows the recovery of these organic materials as fertilizer. There is a wide range of technologies, methods, and experiences for composting in developing countries (Aina 2006). The current challenge is to define the most appropriate technique at small, medium, and large scales, considering local social and economic aspects.

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For this reason, in recent years, we see that waste composting has experienced a revolution worldwide due to its environmental and agricultural benefits. Indeed, composting is considered the best method of valorizing biodegradable waste (Guermoud et al. 2009; Güiza et al. 2015). On the other hand, compost is used as a soil amendment to improve soil quality, stimulate plant growth, and control pathogens and pollutants (Hiarhi et al. 2017; Barbara et al. 2015). Many studies have been conducted in this context to optimize the waste biodegradation process by modifying techniques and operating conditions. Chorolque et al. (2021) suggested composting onion waste as a circular economy in onion production regions. It helps to reduce the amount of waste in the onion production industry and helps reduce the phytopathogen fungi, and serves as an organic fertilizer. Pallejero et al. (2021) reported that applying quality onion residue compost mixed with cow manure gave similar results to chemical fertilizer (using 80 mg ha^{-1} of compost). The unfertilized control was significantly lower than organic and chemical fertilizers.

In Algeria, for example, the situation is different concerning waste composting, which is still traditional and far from being industrialized. This is due to several factors such as the choice of techniques, the price of treatment, the seasonality, and especially the nature of the substrate, which is constantly changing and consequently raises concerns among investors about the progress of the process and the quality of the compost produced. In 2017, 14 million tons of waste were produced in Algeria with a recovery rate by composting not exceeding 1%, according to the national waste agency. Dahmane and Hadjel (2012) and Tahraoui Douma and Matejka (2016) revealed that household waste in Algeria is composed of a large amount of fermentable waste and has never reached a value below 50%. Daily, 20 to 30 tons of fermentable waste is produced only at the wholesale market of fruits and vegetables in the Wilaya of Oran, and ten tons of coffee waste is destined to be disposed of in the household waste landfills.

According to the Mode of Characterization of Household Waste (MCHW), the characterization of municipal solid waste in western Algeria revealed that even small fractions contain a significant amount of organic matter (Derias et al. 2020). Despite all this richness in biodegradable waste, 99% is rejected and directed to landfills in the best case (Bouhadiba et al. 2014). A collaboration between R20 MED (20 Regions for Climate Action) and the Ministry of Environment in the framework of environmental protection and waste management was conducted. Three different experiments on composting green waste (collected from the wholesale market) were carried out and gave good results.

However, there has been no strategy for valorizing the fermentable fraction of waste in Algeria until now. From which the industrialists and investors are questioning the quality of the compost according to the change of the substrate. This study aims to explore the evolution of the physicochemical and microbial characteristics of six different types of waste substrates to understand the impact of the nature of the substrate on the development of the biodegradation process and its impact and influence on the quality of the final product.

Material and methods

Substrates nature and composition

The substrates used in this study consisted of different types of waste, each from a different source. The aim was to study the biodegradation process of several types of waste, the most generated in Algeria and household waste, to better understand the phenomenon and see the feasibility of recycling organic waste by composting. In the first stage of the study, the characterization of municipal solid waste was carried out. The sorting by category and size of the municipal solid waste of the city of Oran was performed using different sieves (100 mm, 20 mm, and 8 mm).The sorting was performed on 13 categories of waste according to the Method of Characterization of household waste MODECOM as described by Derias et al. (2020).

The fermentable fractions from each sieve were collected separately and composted in windrows. They are indicated in Table 1 as C4, C5, and C6; the other three substrates were collected from different areas of Oran.

Technical and operational conditions

The technique used for waste composting is composting in triangular windrows with aeration and systematic turning.

Research conducted by Souabi et al. (2007) and Aina et al. (2012), and Tahraoui Douma (2013) indicated that this is the most widely used technique in the

Table 1 Composition and source of materials used in the composting process

Substrate	Composition	Source
C1	Green waste (vegetable and fruit remains, mixed with tree branches)	El-Karma wholesale market (fruit and vegetables), Oran
C2	Coffee waste	Cafeterias and tea rooms in Bir-El-Djir, Oran
C3	Humus	Hassi Bounif nursery, Oran
C4	Household waste	Putrescible fraction resulting from the characterization of household waste carried out in a previous study (Derias et al. 2020) and having a diameter greater than 20 mm.
C5	Small waste 8mm <f<20mm	Fraction of waste resulting from the characterization of household waste carried out in a previous study (Derias et al. 2020) and having dimensions between 8mm and 20 mm.
C6	Ver y small waste f<8 mm	Fraction of waste resulting from the characterization of household waste and having dimensions smaller than 8 mm

world for composting different types of waste. Thus, it was necessary to study different composting conditions such as nature and composition of the substrate, frequency of turning, and water supply. The literature review indicates that turning is essential not only for oxygen supply during the thermophilic phase but also to maintain the temperature and cool the substrate to reduce overheating (Mustin 1999; Kumar et al. 2015; Shi-Peng et al. 2017; Orhan et al. 2020).

For this purpose, we opted for a daily turning frequency at the beginning of the process and then twice a week during the thermophilic phase and a weekly turning during the cooling and maturation phases. Maintaining the moisture level is essential for a successful composting process, so the moisture level was maintained by using tap water as needed. Visual observation and manual testing were in-situ indicators of the moisture level in each windrow.

Biomass preparation

For substrates C4, C5 and C6, the biomasses were prepared directly after completing the waste characterization at the Hassi Bounif landfill. The substrates were collected and transferred to the Hassi Bounif nursery located 6 km west of the landfill. Each substrate was well mixed and then shaped into a triangular windrow on a platform covered with a plastic sheet. A quantity of 30 kg of C2 substrate was randomly collected from the cafeterias of Bir Eldjir municipality, sieved through a fine sieve to remove impurities and undesirable substances, mixed with a quantity of 10 kg of shredded grass to maintain the necessary C/N ratio, and then swathed.

A quantity of 40 kg of humus (C3) was collected from the nursery and windrowed on the site without adding anything. The humus was used to check its maturity and to compare it to other substrates. Unlike the other substrates, which were all prepared and composted in the same place, the green waste from C1 was composted on the platform of the El-Karma wholesale market parking lot. The substrate was prepared from commercial green waste: 5.5 tons of commercial waste. We took only 30 kg and mixed it with 10 kg of gardening waste for 40 kg of waste. The waste was then shredded and coated in the composting area.

Swath shape and size

Turning was done manually with a shovel and a rake since the quantity was manually maintainable, so the windrows were formed in a small triangular shape of 2 m long, 1 m wide, and 0.5 m high for 150 days during the winter and spring seasons, while respecting the prerequisites to maintain the initial C/N ratio between 20 and 30 and the moisture content of 40% to 60%. The experiments were started simultaneously in six windrows, and systematic sampling was carried out every 20 days according to the method described by Bajon et al. (1994). The C6 substrate was composted as a static windrow because its small quantity did not allow the formation of a triangular windrow. Temperatures were measured daily at different points in the windrows, and their profiles corresponded to the weekly average.

Sampling and analysis of characteristics

In this study, we were monitoring the biodegradation process by determining the number of physicochemical and microbiological parameters listed in Table 2. These parameters were determined from the substrates in their initial state, from the windrows during composting, and from the final products at the end of the composting process. Samples were taken during the process from three areas: the front, middle and back of each windrow to ensure representative results. For each sample, three subsamples were taken and analyzed for accuracy. The experiments were started simultaneously in six windrows, and systematic samples were taken every 20 days according to the method described by Bajon et al. (1994). The mean values were used to analyze the data with the Windows Excel 2010 program in order to construct graphs.

Table 2 Physicochemical and microbiological parameters and measuring instruments

Physicochemical parameters				
Parameter	Sample source	Measuring instrument	Method	Unit
Temperature	Initial substrate During the composting process Final product	Digital thermometer	-------	°C
CO_2 content		CO2 meter	Direct measurement	%
Moisture		Oven	ISO 11465:1993	Mass percentage %
pH		Digital pH-Conductivity meter	EPA 9045D	----------------
Organic matter (OM)		Oven	Afnor NF U 44-160	Mass percentage %
Density (D)		Electronic scale	ml sample 100 weight	kg/l
Heavy metals	Final product	Spectrophotometer	NF X 31-151	ppm
Macronutrients		Spectrophotometer	Atomic absorption spectroscopy	mg/kg dry compost
Microbiological parameters				
Microorganism	Sample source	Conditions: culture medium, incubation time, and incubation temperature (Mahdi et al. 2007)		Unit
Aerobic bacilli	Initial substrate During the composting process Final product	Incubation of agar plates for 10 min at 80°C and 72 .h at 30°C		(CFU/G Dry compost)
Total aerobic mesophiles		Plate count agar incubation for 72 h at 30 °C		
Yeast and molds		Potato dextrose agar incubation for 72 h at 30 °C		
Salmonella and Shigella		Lactose broth incubation for 72 h at 30 °C		

Result and discussion

Changes in windrow temperature over time

At the beginning of the process, the temperature increases rapidly. Indeed, aerobic degradation produces heat. As a result, the temperature change is related to the activity of the microorganisms contained in the substrates (Kumar et al. 2015): the more active the microorganisms are, the more heat they produce, which makes the thermophilic phase longer and, therefore the degradation of the organic matter faster (Lu and Sun 2017a). Temperature measurements show that composting green, coffee, and household waste occurs in four phases: the mesophilic phase from day 0 to day 40. During this phase, soluble and easily biodegradable organic compounds are destroyed and transformed by mesophilic microorganisms (Manios 2004), the thermophilic phase from day 40 to day 80, where mesophilic microorganisms become less competitive and thermophilic microorganisms take over (Margaritis et al. 2018) and the cooling and maturation phases since day 80. The most active substrate is green waste, whose temperature reached a maximum value of 62°C after eight weeks of biodegradation. This shows that the pile is rich in nutrients necessary for the microorganisms.

These results are similar to the works already done in the same context, such as Tahraoui Douma (2013); Shi-Peng et al. (2017), and Lu and Sun(2017b) in terms of the number and order of the phases, but differ in the time and duration of each phase. Indeed, in our research, the mesophilic phase lasts longer compared to the other research works. This may be due to the weather conditions and composting conditions. The composting of small waste is done in two phases: mesophilic and maturation, which is explained by the low nutrient rate, compared to the needs of microorganisms. The very small waste underwent mesophilic biodegradation throughout its transformation due to the very low concentration of microorganisms and nutrients considering their composition and origin. The evolution of the temperature of the humus shows that it is in a maturation phase (Fig. 1).

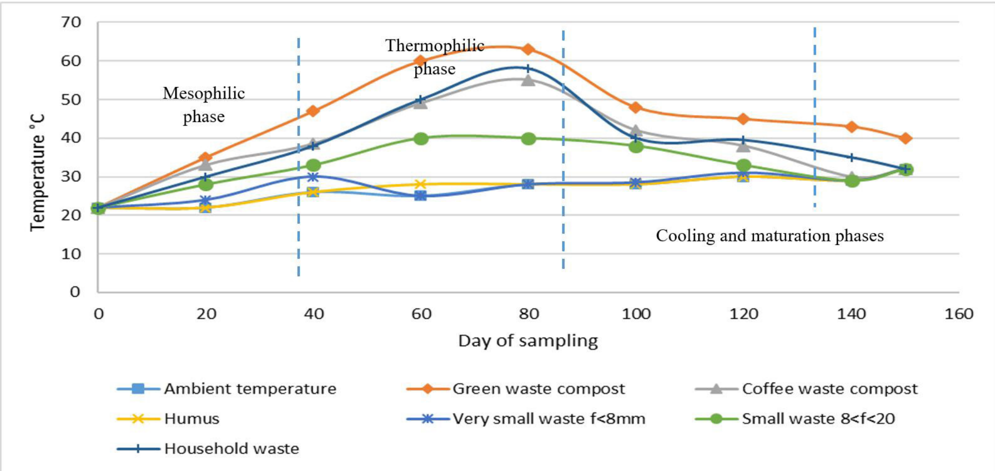

Fig. 1 Temperature changes during composting of six different waste types

pH evolution

The pH is a good indicator of composting progress, and it has a direct relationship with nitrogen loss (Kumar et al. 2016). The theoretical form of pH evolution during composting varies between 5 and 9, passing through the initial acidification phase (Tahraoui 2013). The pH values of C1, C2, C5 and C6 piles followed the theoretical form starting from the acidification phase and the decrease of pH values during the mesophilic phase (Fig. 3). This decrease is related to the transformation of organic compounds into organic and fatty acids (Gajalakshmi and Abbasi 2008) and the conversion of organic nitrogen into ammonium NH_4^+ (Ling et al. 2018). During the thermophilic phase, the pH values of the cited piles increase from between 6.1 and 7.2 to 10.1. This finding could be explained by the consumption of organic and fatty acids by microorganisms (Mustin 1999); which are very active in the pH values between 7.5 and 8.5 (Vijayalaxmi and Mohee (2011)), and/or the conversion of NH_4^+ to volatile NH_3 or NO_2^- /NO_3^- (Ling et al. 2018).

Askari et al. (2020) gave a relationship between the initial protein content of the substrate and the mineralization index. Indeed, substrates containing animal tissues lead to a higher mineralization rate than those containing only plant tissues. In terms of figures, Ebid et al. (2007) found that the mineralization rates of compost produced from kitchen waste, coffee waste, and tea leaves were 38.6%, 9.10%, and 5.25%, respectively. The nitrogen content of the final product could also be affected by the porosity and adsorption capacity of the initial substrate (Lu and Sun 2018). The pH of the humus pile remained basic during the process, which confirms the maturity of the substrate (Fig. 2). The household waste pile did not respect the theoretical shape. The acidification phase at the beginning is not noticed like the other piles. This could be explained by the fact that the biodegradation started long before the formation of the pile, knowing that the collection of the waste by the authorities, the sorting, and the formation of the windrow take 24 h to 36 h.

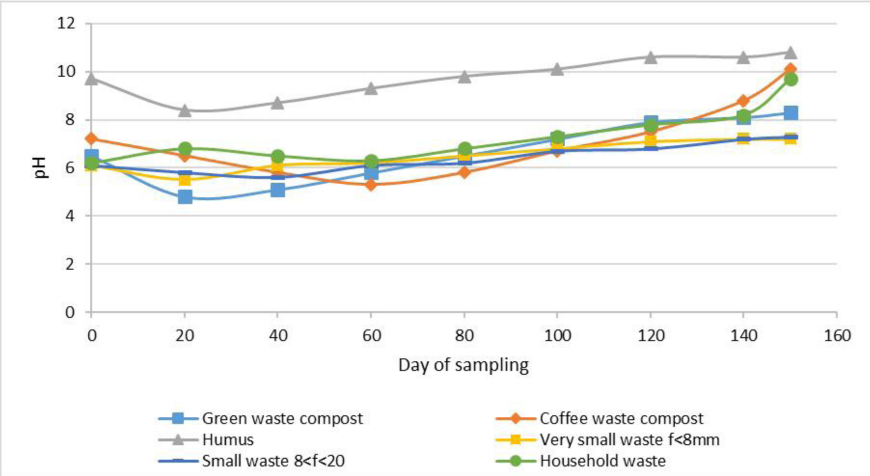

Fig. 2 Changes in pH values during composting

Moisture evolution

Fig. 3 shows that the initial moisture level is 33% for hummus. It increases up to 48% due to watering without evaporative loss, which could be explained by the low rate and activity of microorganisms or low concentration of organic matter and nutrients, so watering was stopped after recording this value for this windrow. Higher initial moisture values were recorded for the other windrows, with the domestic windrow having the highest value (62%). This is due to the nature of the substrate, which contains mainly fruits and vegetable waste. Lasaridi et al. (2006), Andersen et al. (2010), Tahraoui and Matejka (2016), and Margaritis et al. (2018) recorded similar values of moisture in the household waste and household compost. Mustin (1999) explained that this moister could be present in organic particles and gap spaces in the substrate.

During the thermophilic phase, a large amount of moisture necessary for the activities of microorganisms is lost through evaporation due to high temperature and windrow inversion. This requires maintaining the moisture content between 40% and 60% by watering. A value higher than 60% creates anaerobic conditions, and consequently, an anaerobic transformation of the material and a value lower than 40% leads to premature dehydration of compost (Arashiro et al. 2002; Lasaridi et al. 2006). The changes in moisture content show the effect of the nature of the substrate on the moisture content during the biodegradation process; the higher the porosity of the substrate, the smoother the moisture evolution. This is the case of coffee waste in the final stage of the process, the moisture content dropped to a low level, and this could be a good indicator of the maturity of products.

Organic matter and CO_2

The organic matter content during composting varies with the same curvature for green waste (Fig. 4), cof-

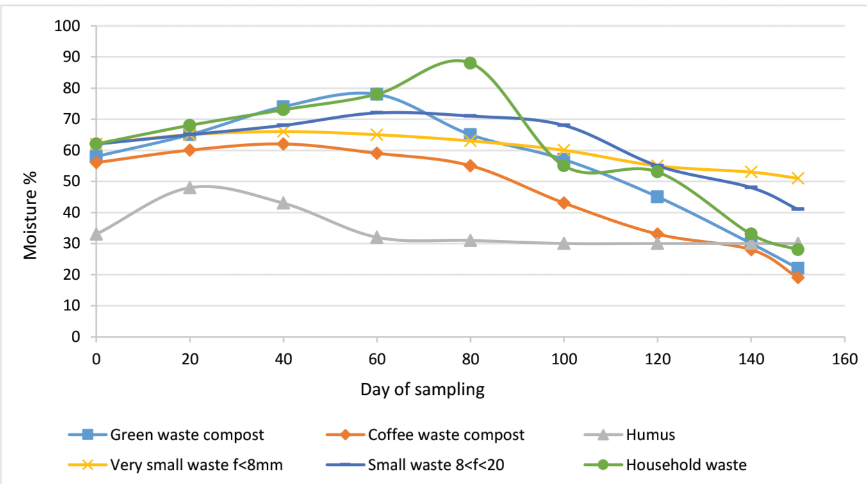

Fig. 3 Moisture changes during composting

fee waste, household waste, and small waste passing through a mineralization phase followed by a deceleration and stabilization phase, it decreases from 92% to 20% for coffee waste, 80% to 19% for household waste and 62% to 19% for green waste and small waste (Fig. 4), making coffee waste composts ideal according to NFU 44-051. Carbon undergoes two main transformations during composting. A large part is transformed into H_2O, CO_2, and energy at the beginning of the process. The rest is gradually transformed into stable humid matter (Kumar et al. 2015). Humus and very small wastes retained almost stable values. This is due to the humification of carbon for the former and the low content of organic matter and microorganisms responsible for biodegradation for the latter.

The degradation of organic matter requires consuming a volume of oxygen and produces the release of half of the volume of oxygen consumed into CO_2 (de Guardia et al. 2010). The rate of CO_2 released indicates the activity of the bacteria compared to the oxygen supply: the graphs of coffee waste, green waste, and small waste have the same appearance. The results show that the level of CO_2 increases during the first 80 days from 12% up to 25% (Fig. 6). This indicates that the microorganisms took time to biodegrade the organic matter. Margaritis et al. (2018) demonstrated that adding minerals to the substrates at the beginning of the process can accelerate the biodegradation of organic matter, as it improves the porosity, oxygen access, and moisture content.

Lu and Sun (2018b) confirmed that composting conditions such as the addition of additives could affect microbial activities to degrade organic matter. The CO_2 level decreases despite turning the piles after the 80th day, indicating that the substrates have entered a matu-

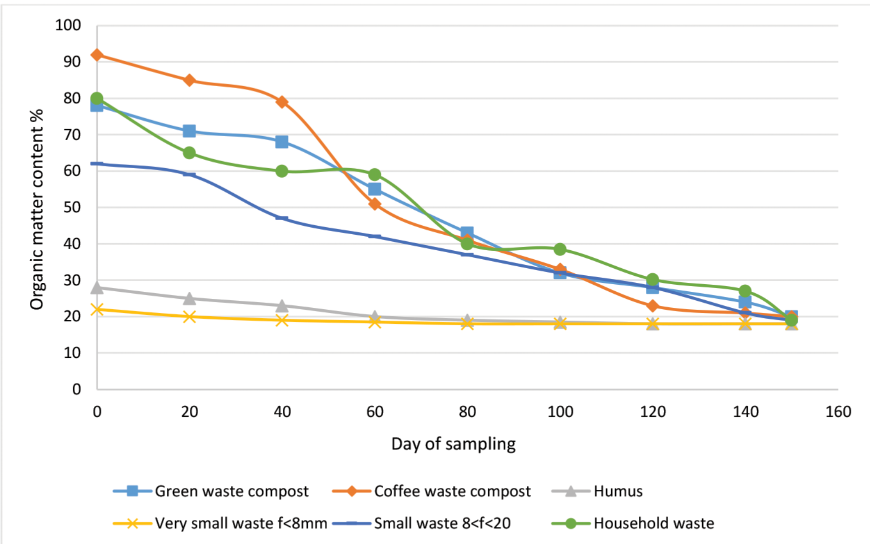

Fig. 4 Changes in organic matter values during composting

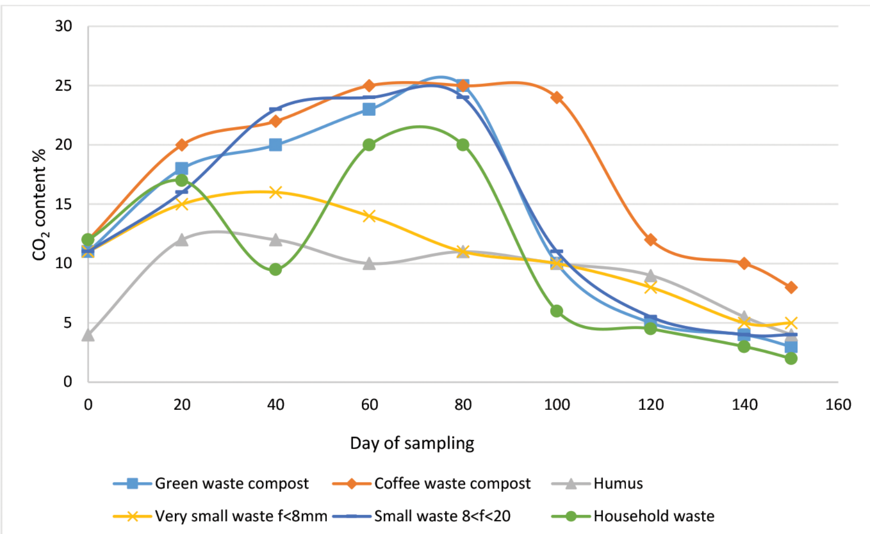

Fig. 5 Changes in CO_2 content during composting

ration phase. For household waste, two important peaks of CO_2 release are noticed, the first one on the twentieth day with a rate of 17%, which means that the microorganisms were very active at the beginning of the process after the 1st turning and the second one during the 60 and 80th days with a maximum rate of 20% (Fig. 5). We can say that it is the most active phase of the biomass biodegradation process.

Density evolution

The change of density is inversely proportional to changes in granulometry during composting. At the beginning of the biodegradation process, the household waste and green waste substrates had an average density of 0.3 kg per liter. This is due to the large particle size, which was between 20 and 100 mm. For coffee waste, small waste, and very small waste, the initial density value was 0.6 and 0.77 kg per liter, which is also due to the particle size and particle size below 20 mm. During biodegradation, the particle size decreases, and the density increases until stabilization in the final phase of the process, reaching a value of 1.15 kg per liter for coffee waste and between 0.8 and 1 kg per liter for the other substrates. Humus did not undergo a great change in density since it did not undergo significant biodegradation or change in granulometry (Fig. 6).

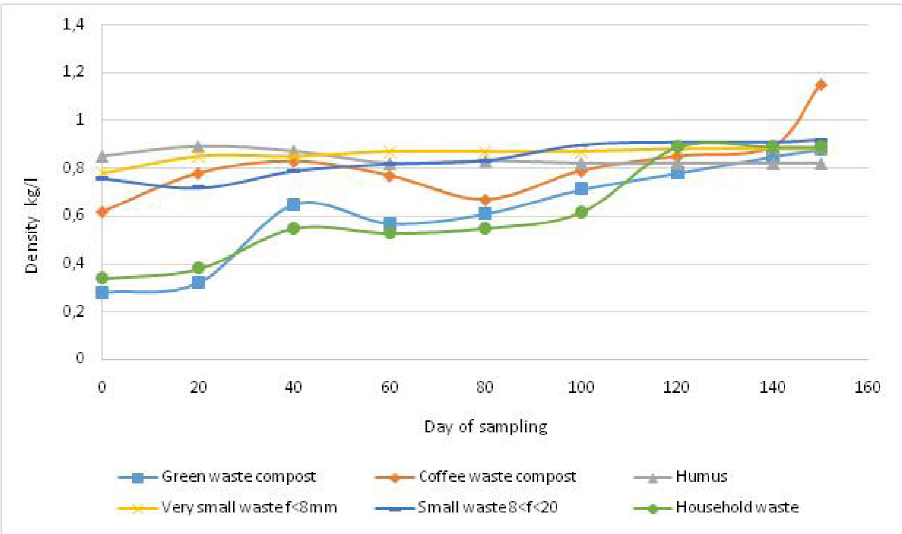

Fig. 6 Density changes during composting

Macronutrients and heavy metals

The content of trace metal elements in the substrates after composting varied from one product to another; Cr, Pb, Zn, and Hg did not exceed the limit value that appears in the international standards cited for all substrates (Table 3). Humus, household waste, and green waste compost complied with the Cd limit value. At the same time, the other substrates exceeded the Cd limit value, which may be caused by the presence of NiCd battery waste and Cd-stabilized plastics (Pamela and Tucker 2008). The very fine wastes exceeded the limit value for Cu content of the French, Canadian and British standards. The source of the Cu in this waste is unknown. The retention of some heavy metals in substrates increases with the rate of organic matter. Edem et al. (2011) and Guangchun et al. (2019) revealed that it is during the thermophilic phase that dissolved organic matter subfractions redistribute heavy metals. Compaoré and Nanéma (2010) reported that regular soil improvement with composts contaminated with heavy metals presents a quality risk considering the half-life of these metals (Cu: 2300 years, Pb: 860 years, and Zn: 2100 years). Household waste composting can also produce a large amount of leachate that can be contaminated with many types of heavy metals (Genevini 1997; Lopes et al. 2011; Chu et al. 2019), if food waste is mixed with some materials associated with food consumption such as plastic (Manfredi et al. 2010). The toxicity of heavy metals, even present in low concentrations, can be affected by seasonality and requires significant treatment loads (Chu et al. 2019).

The nutrient content depends on the nature of the substrate. The results of the macronutrient analysis show that composts contain high contents of P, Mg, and Ca (Table 4). The richness of mineral elements such as

Table 3 Heavy metal content (ppm) in ripe composts

Parameter	Cr	Pb	Cd	Cu	Zn	Hg
Coffee waste compost	2.249	3.33	2.59	57.708	58.513	0.009
Humus	10.588	9.628	0.655	44.551	61.666	0.017
Very small waste f<8mm	9.203	20.345	3.219	479.945	187.553	0
Small waste 8<f<20	1,862	7.725	2.648	35.397	150.827	0.026
Household waste	0.67	2.937	4.212	113.922	130.879	0.012
Green waste compost	28.574	7.678	1.15	122.714	106.646	0.015
NF U 44-051	120	180	3	300	600	2
Chinese standard [a]	150	50	3	-------------	----------	2
Canadian standard [b]	210	150	3	400	700	8
British standard [c]	100	200	1.5	200	400	1
American standard [d]	-----------	300	39	1500	2800	17

[a]: Organic fertilizer standard (NY 525, based on manure, plant/animal residues and/or by-products), China Ministry of Agriculture, 2012.

[b]: National Compost Quality Standard (CAN/BNQ 0413-200, Category A - Compost for all applications, Canadian Council of Ministers of the Environment, 2005.

[c]: Standard: PAS 100, European Commission, SWD (2016) 64/F1-EN, 2016.

[d]: Code of Federal Regulations-Part 503: Standard for the Use of Sewage Sludge (CFR 503.13), Environmental Protection Agency of USA, 2015.

P, Ca, and Mg allows the composts produced to act as fertilizers. Still, their main effect is on the soil's physical, chemical, and biological stability (Bertoldi et al. 1983).

Table 4 Macronutrient content (mg / kg) of ripe composts

Parameter	Ca	Mg	P
Coffee waste compost	618.126	6.8	475.41
Humus	4629.56	11.833	397.47
Very small waste F<8mm	3238.84	15.062	615.38
Small waste 8<F<20	3191.31	11.097	678.7
Household waste	3094.41	6.721	414.29
Green waste compost	4824.72	13.799	640.6

Bacilli and total aerobic mesophilic

The evolution of bacilli is remarkable for coffee waste, green waste, household waste, and small waste (Fig. 7). The bacterial load increases during the mesophilic and thermophilic phase until reaching a value of 110×10^8 CFU/g dry compost for fine waste after the 80th day of composting, 230×10^8 CFU/g dry compost for household waste after the 60th day, 250×10^8 CFU/g dry compost for green waste after 80th day and a maximum value of 270×10^8 CFU/g dry compost for coffee waste after 80th days (Fig. 7). The bacilli are active during the mesophilic and thermophilic phases of composting. Their concentration decreases over time during the stabilization and maturation phase. Similarly, for aerobic mesophilic bacteria, the evolution is remarkable for green waste, coffee waste, household waste, and small waste. The bacterial load increases during the mesophilic phase until it peaks after the 40th day for all substrates. This peak has a value of 3.5×10^6 CFU/g dry compost for fine waste, 6.9×10^6 CFU/g dry compost for household waste, 8.2×10^6 CFU/g dry compost for coffee waste, and a maximum value of 9.5×10^6 CFU/g dry compost for green waste. Aerobic mesophilic bacteria are active during the mesophilic composting phase. Their concentration decreases over time during the thermophilic, stabilization, and maturation phases (Fig. 8).

Yeast and molds concentration change

The concentration of yeasts and molds is remarkable for coffee waste, green waste, and household waste (Fig. 9). The concentrations of microorganisms increased significantly during the mesophilic phase until reaching a value of 174×10^7 CFU/g dry compost for household waste after the 20th day, 210×10^7 CFU/g dry compost for green waste after the 20th day, and a maximum value of 390×10^7 CFU/g dry compost for coffee waste after 20th day. Yeasts and molds progressively decrease until reaching a minimum value of less than 50×10^7 CFU/g dry compost for all substrates at the end of the thermophilic phase. This is due to their low thermal resistance, which does not allow them to survive in high-temperature environments. During the stabilization and maturation phase, they increase to reach stable values between 56×10^7 CFU/g dry compost and 117×10^7 CFU/g dry compost (Fig. 9 and Fig. 10).

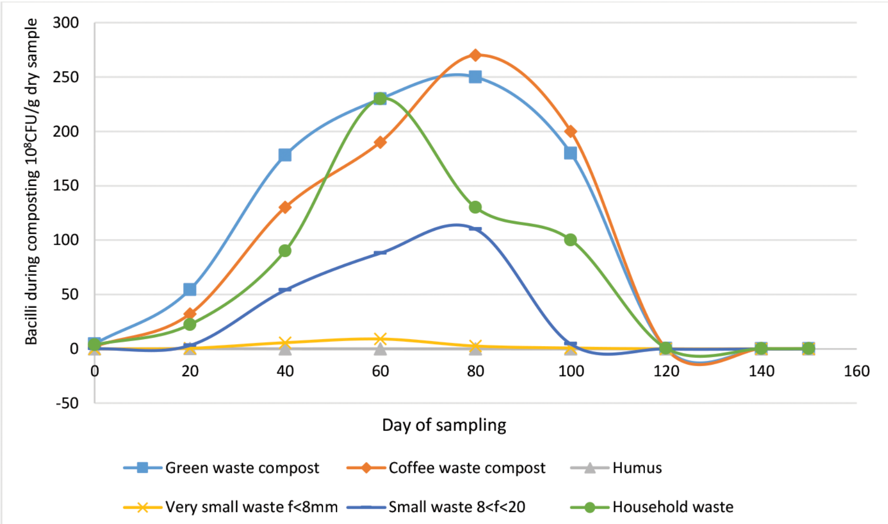

Fig. 7 Effect of the substrate nature on bacilli evolution during composting

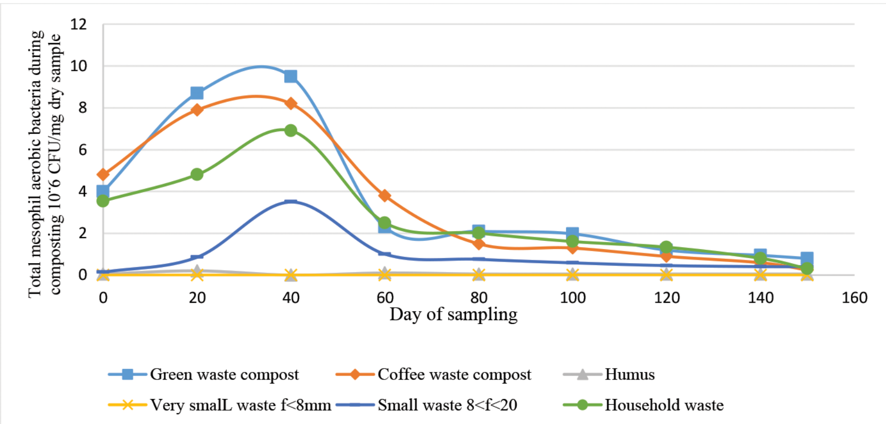

Fig. 8 Effect of the substrate nature on the evolution of total aerobic mesophilic

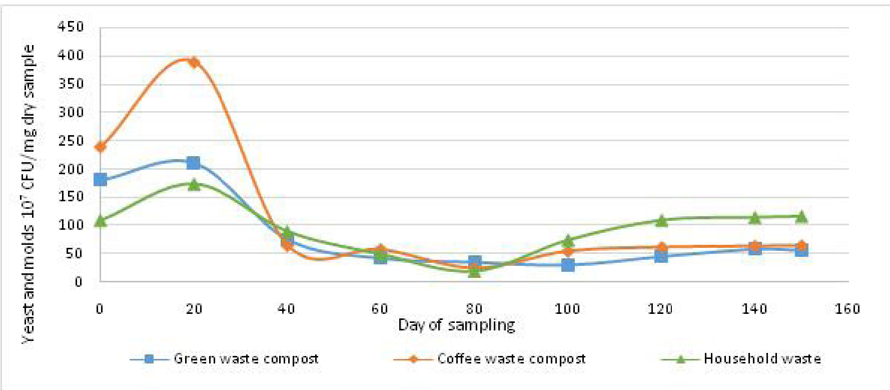

Fig. 9 Effect of the substrate nature on the concentration of yeast and molds during composting for green, coffee, and household waste

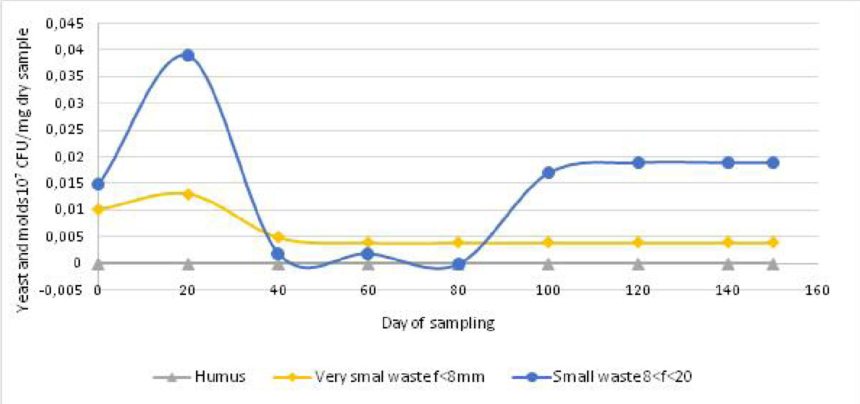

Fig. 10 Effect of the substrate nature on the concentration of yeast and molds during composting for hummus, small and very small waste

Salmonella and *Shigella* concentration change

The concentration of *Salmonella* and *Shigella* tends towards zero for all substrates at the end of composting except for very small waste (Fig. 11). These results are in accordance with the NF U 44-051 standard, which indicates the absence of *Salmonella* and *Shigella* in 25 grams for vegetable crops and the absence of *Salmonella* and *Shigella* in one gram of compost for all other crops.

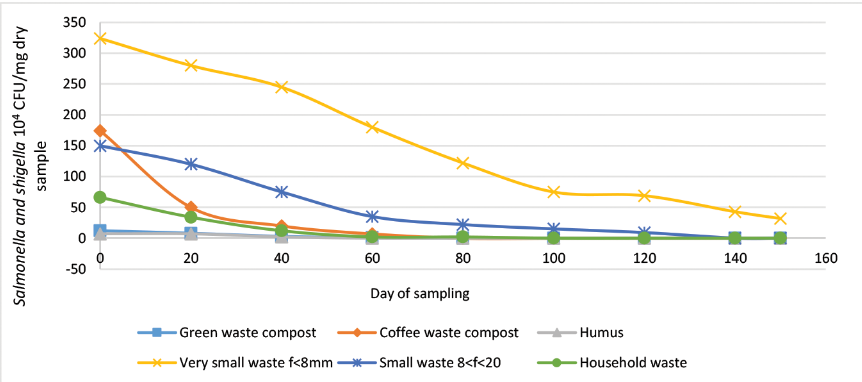

Fig. 11 *Salmonella* and *Shigella* concentration change during composting

Conclusion

The experiments presented in this study showed that green, coffee, and household waste (the putrescible fraction separated from the other fractions) could be considered the best substrates for composting; their physicochemical characteristics evolve similarly and with the same curvature. The rate of heavy metals does not exceed the standards for the three substrates except that the Cd concentration exceeded the British standard for coffee grounds. This is due to incorporating coffee waste with plastic waste; the latter contains Cd as a quality enhancer. The addition of additives can improve the macronutrient content. The evolution of microbiological characteristics is also similar to the three substrates. At the beginning of the biodegradation process, mesophilic bacteria, Yeast, and Molds are involved until reaching the thermophilic phase, where bacilli take over until the slowing down phase as yeast and molds are involved again but in low concentration compared to the mesophilic phase.

The concentration of pathogenic microorganisms such as *Salmonella* and *Shigella* did not exceed the NFU 44-051 standard. The three substrates gave good compost and can be used as organic fertilizer for vegetable crops. By respecting the necessary operating conditions for biodegradation (C/N ratio between 20-30 and moisture content between 40% and 60%), green waste, household waste, and coffee waste can be composted for vegetable crops, but the dosage of heavy metals is preferable beforehand. Small and very small wastes have not undergone the best processing and have not given the best result. They can therefore be used as a soil improver for green areas and public gardens. The results indicate the feasibility and effectiveness of waste vaporization by composting. Other factors such as the effect of seasonal conditions and composting technique need to be explored in future studies to provide more evidence of the benefits described above.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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