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Proof of concept of high-rate decentralized pre-composting of kitchen waste: optimizing design and operation of a novel drum reactor

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Highlights:

A high-rate prototype reactor (200L) to pre-compost kitchen waste was built

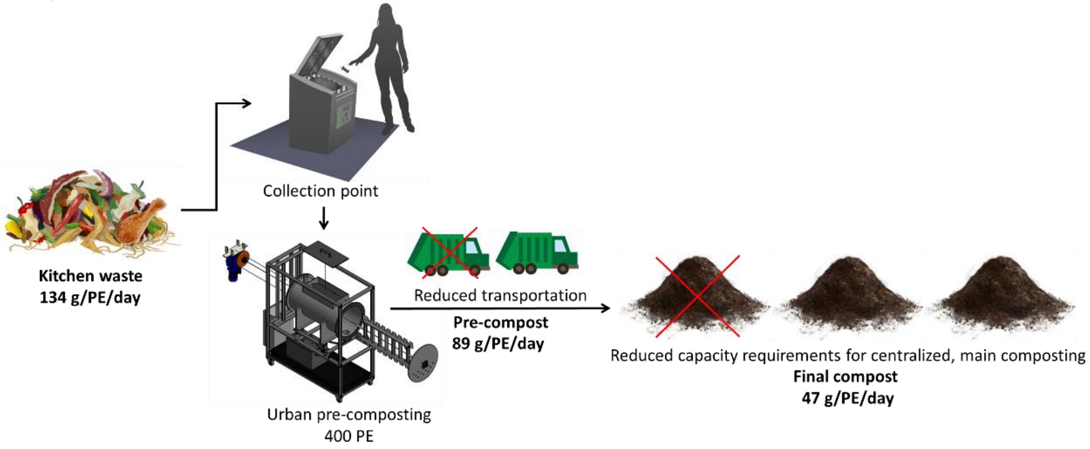
Kitchen waste mass and volume reductions of $33\%_{FW}$ and 62% were achieved

Results indicate a mean total cost of €11,600 per urban pre-composter over 10 years

Final compost with a C/N ratio of 12 was produced from pre-compost in 54 days

No addition of bulking agents or separate leachate collection was required

Graphical Abstract



ABSTRACT

Each ton of organic household that is collected, transported and composted incurs costs (€75/ton gate fee). Reducing the mass and volume of kitchen waste (KW) at the point of collection can diminish transport requirements and associated costs, while also leading to an overall reduction in gate fees for final processing. To this end, the objective of this research is to deliver a proof of concept for the so-called "urban pre-composter"; a bioreactor for the decentralized, high-rate pre-treatment of KW, that aims at mass and volume reduction at the point of collection. Results show considerable reductions in mass (33%), volume (62%) and organic solids (32%) of real KW, while provision of structure material and separate collection of leachate was found to be unnecessary. The temperature profile, C/N ratio (12) and VS/TS ratio (0.69) indicated that a mature compost can be produced in 68 days (after pre-composting and main composting). An economic Monte Carlo simulation yielded that the urban pre-composter concept is not more expensive than the current approach, provided its cost per unit is €8,000–14,500 over a 10-year period (OPEX and CAPEX, in 80% of the cases). The urban pre-composter is therefore a promising system for the efficient pre-treatment of organic household waste in an urban context.

Keywords: food waste; organic household waste; water removal; community scale; source separation; circular economy

Abbreviations: KW = kitchen waste; FKW = formulated kitchen waste; RKW = real kitchen waste; OHW = organic household waste; FW = fresh weight; PE = person equivalents; EC = electrical conductivity; TS = total solids; VS = volatile solids; FS = fixed solids; TSS = total suspended solids; VSS = volatile suspended solids; OC = organic carbon; COD = chemical oxygen demand; BOD_5 = 5-day biochemical oxygen demand; TKN = total Kjeldahl nitrogen; TP = total phosphorus; VFA = volatile fatty acids

1. Introduction

The recent amendment of the Council Directive on the landfill of waste compels European countries to increase municipal waste recycling to 55% by 2025, while organic household waste (OHW) should either be separately collected or home composted by 2024 (European Parliament and Council, 2018). Due to these drivers, the separate collection of OHW, typically followed by centralized composting (Eurostat, 2016; ORBIT/ECN, 2008), has increasingly been implemented. In inner-city locations, separate collection of OHW is challenging and costly. Door-to-door collection of OHW is often not performed, due to space constrains and odor nuisance. Furthermore, costs for waste collection and transport as well as composting gate fees incur costs of about 75€/ton (waste treated for composting) to 87€/ton waste treated (anaerobic digestion - cost for Belgium) (European Commission, 2002). This is particularly important when considering that kitchen waste (KW), the fraction that represents up to 75% fresh weight (FW) of the OHW (EEA/ETC-WMF, 2002; Nair et al., 2006), consists of 67-85% moisture (see section 1 in supplementary material (SM)). Consequently, reducing the moisture content of KW in combination with a reduction of the organic matter will lead to a reduction in mass and volume. This will result in savings on gate fees and lower transport requirements, and as a result, can reduce costs and mitigate problems associated with mobility and odor generation.

As an alternative to door-to-door collection, community-scale collection points are currently implemented in a number of countries (Austria, Switzerland, Germany, UK, Belgium, Netherlands, Sweden and Norway) (OVAM, 2015a; Siebert, 2015).

Collection of organic waste in these containers results in an uncontrolled breakdown of organic matter through anaerobic fermentation leading to common odor problems and leachate generation. While this processes has no negative effects on the valorization of KW through anaerobic digestion, it does not facilitate the more frequent valorization route via compositing due to the compaction, release of moisture in the waste and a resulting low porosity (Sundberg et al., 2011).

The present study puts forward the novel concept of controlling and purposefully manipulating the biological degradation process already at the first point of disposal by preparing a pre-compost that facilitates main composting. Such pre-composting apart from leading to the benefits outlined above, will additionally result in the controlled breakdown of organic matter in the pre-composting stage, reducing time and space requirements at the final main composting stage. This is of relevance as the main composting stage can last between 9-11 weeks if mechanical mixing is applied, and up to 51 weeks under static conditions (Amlinger et al., 2008; Iyengar and Bhave, 2006).

Given the above considerations, the objective of this research was to develop a high-rate bioreactor for decentralized pre-composting of KW and to deliver a proof of concept. Specifically, this study aims at optimizing the operational parameters to achieve a pre-composting system that maximizes the mass and volume reduction as well as reducing the overall composting time. Furthermore, it was the aim of this study to provide evidence for the economic benefits of implementation of a pre-composting reactor in combination with a main composting stage. To the authors' knowledge, it is the first time that the concept of pre-composting of KW at an urban, underground collection point is proposed. To date, only one other study investigated a two-stage composting approach, that was using tumbler bins at the first stage and vermicomposting at the second stage (Nair et al., 2006). This differs markedly from the reactor design of the present research, which made use of a prototype static drum reactor with internal scrapers at the first stage and conventional mainstage composting. The study is conducted at semi-technical scale with a 200L reactor, serving 25 person equivalents (PE), while the envisaged final system should serve 400 PE, intended to be applied in the city of Antwerp.

2. Materials and Methods

2.1 Research approach

The research approach can be structured along three phases: (i) design of reactor and experiments based on literature review, (ii) conduction of experiments and analyses and (iii) evaluation of full-scale implementation. (i) The urban pre-composter reactor was designed following a literature study on the requirements of KW composting. Furthermore, the composition of KW was defined using evidence from literature. (ii) Four pre-composting Runs were then conducted using the designed reactor. Runs 1-3 received KW according to the definition derived from literature and Run 4 received real KW. Main composting was carried out to evaluate the required time to produce a mature product, and to establish the final compost characteristics. The products (i.e. pre-compost and final compost) and the composting process were evaluated according to a number of key performance indicators (mass, volume and volatile solids reduction; C/N ratio; temperature). (iii) Finally, an analysis of the remaining implementation challenges and economic benefits of the combination of urban pre-composter and main composting was carried out. The methodologies underlying this approach are detailed below as well as in the SM.

2.2 Reactor and experimental design

2.2.1 Urban pre-composter design

The urban pre-composter prototype was design as a closed vessel, stationary drum composting system, completely mixed through the use of an internal agitator (non-plug flow), equipped with active aeration (see section 2.3 in SM). The capacity of the prototype was 200L (**Fig. 1**). The static barrel (1) of the experimental set-up was constructed from high-density polyethylene (HDPE), and is supported by a frame (Profile 8 (40x4) nature, ITEM Industrietechnik GmbH). The opening situated at the upper part of the reactor (2) (300 mm x 600 mm) serves as solid organic waste load/unload point (**Fig. 1(a)**). In the full-scale reactor this opening would be designed for disposal with custom made receptacles and it would be sealed with a badge operated lid that is linked to a data logger (the use of a badge systems is already common in many cities). Through this system, the amount of green waste disposed can be minimized by limiting the receptacle's size and by monitoring the disposal frequency. Furthermore, the provision of plastic receptacles should discourage the use of plastic bags.

Aeration of 60 L_{air}/min (1.04-4.37 $L_{air}/kg_{waste\ added}$/min) was provided using an air pump (SilentiaPro 3600, Velda). The 12 perforations situated at the bottom half of the right side of the reactor (3) (diameter of 12.7 mm; **Fig. 1(b)**) serve as air inlet points. This feature was selected for the homogeneous insertion of air in the reactor.

The air outlet pipe (4) (diameter of 50 mm) is situated at the top of the reactor, while at the bottom right of the reactor (5) (**Fig. 1(c)**) the leachate drainage tube is located. The draining system for the leachate is composed of a tube (diameter of 100 mm) containing two sieves with perforations of 5mm and 2mm diameter respectively.

As shown in **Fig. 1(c)** the leachate is collected in the 30L reservoir placed bellow the reactor (6). This reservoir is composed of two parts, the right part serves as leachate collection point, and the left as the container of the liquid used for waste moistening. The dividing wall contains perforations to allow the solid free leachate to pass to the other side of the box, and to be used as a moistening agent. The moistening agent is recirculated using a pulse width modulation controlled diaphragm pump (NF 1.25 RPDCB-4A, KNF) and sprayed on the composted material through a nozzle (7) (Spraying Systems Co., Teejet Technologies) situated at the interior of the reactor (**Fig. 1(c)**). The mixing of the waste is performed through the use of internal agitator (8, 9) made from aluminum, the design of which was adjusted (9) after the conduction of Runs 1-2 (**Fig. 1(d)**). The agitator is rotating through the use of a motor with bevel gear reducer (10) (SK9013.1-71L/4 TF MG45O, NORD Drivesystems). The waste temperature was monitored through the use of four sensors evenly distributed at the bottom of the reactor (Easytemp TMR31, Endress+Hauser AG), and the online data were logged using a programmable logic controller (PLC) (11) (CX9020, Beckhoff).

2.2.2 Formulated and real kitchen waste

The substrate for three of the four experimental runs was strictly formulated using the yearly average composition of KW disposed in the region of Flanders (OVAM, 2015b). Specifically, it consisted of bread (15%$_{FW}$); vegetables (35%$_{FW}$); fruit (35%$_{FW}$); cooked food (6%$_{FW}$); meat, fish and poultry (4%$_{FW}$); dairy products (yogurt) (4%$_{FW}$); sauces, herbs and spices (1%$_{FW}$). The average composition of vegetables consisted of: tomatoes (28%$_{FW}$); carrots (26%$_{FW}$); onions (20%$_{FW}$); potatoes (15%$_{FW}$) and lettuce (11%$_{FW}$). Finally, the average composition of fruit is composed of: apples (30%$_{FW}$); bananas (25%$_{FW}$); oranges (25%$_{FW}$); pears (11%$_{FW}$) and melons (9%$_{FW}$). To produce this formulated kitchen waste (FKW), the fruit and vegetables were peeled and cut, and only the peel and endocarp (if present, depending on the fruit/vegetable) were included in the waste. Small quantities (0.18 kg/day; 5%$_{FW}$ of total waste load) of commercially available sawdust were used for Runs 2-3 in order to test its effect on the structure and porosity to the composted material, achieving a final composition of 20:1 (in FW) FKW:sawdust. This was selected as sawdust is a bulking agent that provides structure and porosity and therefore increases the aeration efficiency (see section 1 in SM). Real kitchen waste (RKW) was obtained from the city of Antwerp and was used as a substrate in Run 4, to evaluate the performance of the pre-composter using this realistic waste stream. A detailed composition of RKW can be found in section 2.2 in SM. All waste components, subsequent to the peeling (FKW) or collection (RKW), were stored at 4˚C after establishing that under these conditions there is no noticeable alteration of the characteristics of interest (<5%) after 2 weeks of storage (duration of the experiments).

2.3 Experimental conditions

2.3.1 Pre-composting

The specific operational parameters of each experiment are presented in **Table 1**. The bioreactor was operated at fed-batch mode, mimicking a simplified waste disposal behavior of the citizens. The waste was loaded once every two days into the bioreactor (specific quantities are illustrated in **Table 1**), and the duration of all runs was 14 days. The choice for the two-week interval was based on the objective to reduce transport costs of KW collection. Current collection of organic waste in the case study of Antwerp takes place on a weekly basis to enable odor control and to overcome capacity problems. In all Runs, with exception of Run 1 a part of the pre-compost of the previous Run was used as an inoculum (10% in FW of the total waste loaded - **Table 1**).

Aliquot samples were extracted before and after waste feeding as well as at the initiation and termination of the experiments. The pH, total and volatile solids (TS and VS) and bulk density were determined in all samples, whereas chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP) and potassium (K) were measured at the beginning and end of each experiment. The analytical techniques are described in detail in SM (section **2.4**). The overall mass was determined at the beginning and end of all Runs, as well as in twice per week for Runs 2-4 (in Run 1 it was only determined on day 6) via emptying the reactor and weighing its content.

2.3.2 Main composting

A batch main composting step was performed on the pre-compost obtained from Run 2. The goal of this step was to establish the treatment needs of the substrate to produce a mature product. The experiment was performed under pile composting conditions using a 40L container. Spherical macroporous inert carriers (diameter of c.a. 2 cm) were used to provide structure and better air penetration in an initial ratio of 6.63:1 pre-compost:carriers. The aim was to mimic the conditions in a centralized composting plant, where the pre-composted waste would be mixed with bulky material (e.g. garden waste). The substrate was mixed every 1-3 days and forced aeration was provided using an air pump with a flow rate of 5.2 L_{air}/min (0.27 $L_{air}/kg_{waste\ added}$/min) using a diaphragm pump (model 300, WISA GmbH). The pH, TS, VS and bulk density were determined throughout the experimental period, while COD, TKN, TP and K were measured at the beginning and end of each experiment. The overall mass of the compost was determined throughout the experimental period.

2.4 Economic evaluation of full-scale implementation

The economic benefits from the implementation of urban pre-composting have been benchmarked against the costs of implementation of community scale, decentralized collection. The assessment aimed to evaluate potential cost savings from transport and collection fees only. In this manner the assessment is used to estimate the potential costs the construction and operation of an urban pre-composter may incur over a 10-year period. The results are presented as the “potential costs of urban pre-composter”, which include the reduction of the gate fee, reduced cost for transport and labor as well as the avoided investment into a conventional container (€ 4,000 per container at 3 m^3). The cost reduction have been determined as net present values over the 10-year period, with a discount rate of 5 %.

The assumptions underlying this calculation are based on information of the Flemish Waste Authority (OVAM, (2014); **Table 2**) and are purely based on mass reduction, while volume reductions are not accounted for. The values used are the mass reduction achieved during different experimental runs (see **Table 4**). However, Run 4 (33% mass reduction) with real waste stream (RKW) should be considered the most probable scenario as it is carried out on waste that will likely be received by the pre-composter.

The calculations are taking into account the direct costs associated to transportation (i.e. fuel costs and annual cost of the truck, including insurance and maintenance) and gate fees payable at delivery of KW to the waste processor. The gate fee assumed is the current fee for OHW waste charged in Belgium (€75). To account for organic matter reduction of KW and a resulting reduced composting time (see also section **3.5**) it is assumed that the gate fee is reduced by 25%, from €75.0 to €56.3. It should be noted that the gate fee reduction is based on the VS removal, which in all cases exceeds 25%. Costs are modeled for an installations that receives the KW of 400 people living in an urban setting. The amount of people served was selected based on the current population density of 2,500 PE/km^2 (Wikipedia, 2018) in the city of Antwerp where the system is intended to be applied, assuming a distance of 0.20 ± 0.04 km between collection points (**Table 2**). The waste received is estimated from the mean KW production in Antwerp of 0.062 t/person/year and assuming a

80% collection of this KW (0.05 t/PE/year). The value for KW production compares well to data for Europe of an average production of 0.065 t/person/year (Malta excluded as it is considered an outlier) (Stenmark et al., 2016). This assessment excludes non-monetary benefits arising from implementation of the pre-composting concept related to environmental impact mitigation (e.g. reduced emissions from transport, less odor problems, traffic reduction). To explore the potential for implementing urban pre-composting in areas with different cost characteristics, and to account for possible deviations from the assumptions made, a sensitivity analysis has been carried out. This was executed through 1,000 Monte Carlo simulations, with a variation of 20% to the variables (uniform distribution) indicated in **Table 2** (for details on the methodology used see section 2.5 in SM).

3. Results

3.1 Solid waste characterization

Table 3 shows the characteristics of FKW and RKW, with the key features being the notably low pH (4.28-4.96) and high moisture content (69.2%-74.4%). The low pH values are attributed to the presence of fruit and vegetables (namely apple, banana, orange, pear, tomato, and carrot) that have a pH between 3.1-5.2. The main contributors to the high moisture content were the fruit and vegetable residues, with 85.2 ± 1.5$\%_{FW}$ and 88.5 ± 1.5$\%_{FW}$, respectively. When 5$\%_{FW}$ sawdust was added (Runs 2-3; moisture content of sawdust 6.93%), to provide structure and absorb water, the moisture content reduced to 66$\%_{FW}$. Furthermore, 97% and 88% of the total solids (TS) consisted of volatile solids (VS) for FKW and RKW, respectively. RKW presented a lower C/N ratio (25.4) compared to FKW (31.5) due to its lower carbon content. The addition of sawdust, which mainly consists of organic carbon (50%$_{FW}$) and is characterized by a low TKN and TP content (leading to a C/N ratio of 843; **Table 3**), resulted in a C/N ratio of 36.1. Finally, RKW presented a higher level of compaction, with the wet density being 33% higher than that of FKW, due to its higher decomposition extent.

3.2 Pre-composting process performance

3.2.1 Mass reduction

Total mass reductions corresponded to 22, 25, 30, and 33%$_{FW}$ (32, 33, 37, and 28%$_{TS}$ reduction) for Runs 1-4 respectively (**Table 4**; **Fig.2** in SM). The largest part of this reduction was due to the removal of water (7.5-14 kg). More specifically, the biggest contribution was from water evaporation (19, 21, 27, and 36% of the overall mass reduction for Runs 1-4, respectively), while there was a minor contribution from leaching (0.30, 0.55, 0.55, and 1.01%, respectively). Despite the water removal, the moisture content ranged between 56.4 ± 1.9 and 75.1 ± 1.2%. Consequently, there was no need for moistening as the water content remained always above the set target value for compost moisture of 55% (Komilis and Ham, 2003; Nair et al., 2006).

The VS reduction was between 41 and 43% for Runs 2-3, while it was lower for Runs 1 and 4 (35 and 32% respectively). Runs 2-3 presented the highest VS removal rate (2.7-2.8 $kg_{VS}/m^3_{reactor}/day$; corresponding to 41-43% VS removal), due to the higher degradation of organic carbon as a result of the optimization of the system’s design and operation leading to more efficient aeration (**Table 1**), while the lowest value was presented in Run 4 possibly due to the removal of highly degradable matter before the collection of RKW.

3.2.2 Volume reduction and bulk density increase

Fig. 2 depicts the changes in volume and density throughout the experimental period. The volume reductions achieved were 57, 57, 59, and 62% for Runs 1-4, respectively (**Table 4**). During Run 1, the mixing intensity was adjusted after 3 days of operation as the initial intensity resulted in a waste with a notably high density and reduced porosity, which would hamper the composting process. The addition of sawdust (Runs 2-3) resulted in higher density increase (see **Table 1** in SM). Furthermore, sawdust did not markedly affect the final density, as Runs 1-3 resulted in comparable final values (983.4-1011 kg_{FW}/m^3) (**Fig. 2**). Therefore, sawdust can be omitted, as it did not have, as expected, a beneficial effect in providing structure in this system as well as reducing the density of pre-compost. For RKW, the increase in density was lower compared to FKW, as the initial waste had a high initial value (900 kg_{FW}/m^3) (**Table 3**), probably due to the degradation of biomass and the associated release of moisture and compaction. It should be noted that values exceeding 900 kg_{FW}/m^3 are a relatively high (Sundberg et al., 2011), and are the result of the mechanical mixing, the high moisture content of the feedstock (**Table 3**), as well as the increase of moisture content throughout the experimental period (**Table 5**).

3.2.3 pH, temperature and leachate production

The pH of pre-compost showed values between 3.8-4.2 after 14 days of composting (see **Fig. 3** in SM). The additions of base and sawdust were insufficient to compensate the drop in pH. The same pattern was present in all runs, regardless of the initial pH value (4.5-8.0).

The fed-batch feeding mode of a high moisture content waste, coupled to the intensive mixing and forced aeration resulted in mesophilic temperatures in Runs 2-4 (22-36°C). Only Run 1 showed slightly lower temperatures (17-23°C; see **Fig. 3** in SM), likely due to the lower conversion efficiency and the lower ambient temperature.

The total leachate amounted to 115, 205, 207, and 384 mL, which correspond to only 2.1, 3.6, 3.7 and 7.3 mL/kg$_{FM}$. More information on leachate characteristics can be found in section 3.2 of SM.

3.3 Main composting

After 54 days of main composting (overall composting of 68 days), the total mass of the pre-composted waste was reduced by another 47%$_{FW}$, the VS by 62%, and the volume by 53%. Hence, this phase contributed to the overall reductions by 58%$_{FW}$, 47% and 29%, for mass VS, and volume respectively, in 79% of the composting time. The VS removal rate was 47% lower in comparison to pre-composting of Run 2 (**Table 4**). This was expected as the main composting set-up did not allow the realization of high rates. It should be noted that sawdust is not expected to contribute to the mass and volume reduction during the experimental period (i.e. 68 days) since decomposition time of c.a. 6 months has been reported (Kostov et al., 1991).

Interestingly, the wet bulk density starting from 963 kg/m^3 did not further increase. Hence, in this case there was no considerable contribution from compaction to the observed volume reduction (**Fig. 3**), as opposed to the increasing trend observed in the pre-composting stage. The reduction of water content, TS and VS was 45, 54, and

62% (**Table 4**), while the FS content remained at roughly the same levels (see **Fig. 2** in SM). The pH increased from 4.1 to 9.7 (see **Fig. 3** in SM). The temperature of the system rapidly increased during the first week of composting and was situated in the thermophilic range (>45°C) on days 7-15, with the highest value of 51°C achieved on day 9 (see **Fig. 3** in SM). It subsequently decreased to values of roughly 30°C, where it remained for the rest of the experimental period. The produced compost is considered to be mature, given the stability of VS and TS levels, the low VS/TS ratio (0.69), the low carbon to nitrogen ratio (C/N=12), as well as the lower temperature of the pile (see **Fig. 3** in SM), which was equal to the ambient (**Table 1**), during the last two weeks of the process.

3.4 Quality of pre-compost and matured compost

After a period of 14 days, the C/N ratio reduced from an initial value of 32 to 23 in Run 1, from 36 to 25 and 29 in Runs 2-3 respectively, and from 25 to 19 in Run 4 (**Table 5**). The TS, VS, COD, and OC content reduced due to the decomposition of biodegradable organic compounds. An indication of the content of organic solids is the VS/TS ratio, which also reduced throughout the experimental period. On the other hand, the FS content increased due to the reduction of organic solid content. Therefore, it is indicated that microorganisms were actively degrading organic matter. The pH of the pre-compost was between 3.8-4.2, even if the input material had a pH higher than 7 (Run 3). This is due to the short composting period and does increase during maturation (see section **3.3**). TKN ranged between 0.48 and 0.57$\%_{FW}$, while TP and K were in the range of 0.05-0.10$\%_{FW}$ and 0.04-0.07$\%_{FW}$, respectively.

The moisture content was between 69 and 73%, showing only a small decrease from its initial value.

After the main stage composting a C/N ratio of 12 was achieved (**Table 5**). This is the result of the pre-composting in combination with a main composting step at pile conditions with forced aeration and daily mechanical mixing. TS, VS, and OC decreased, while COD content was reduced by 39%. The decomposition of organic matter is also indicated by the reduction of the ratio VS/TS. The VS/TKN ratio further increased by 59% due to the higher VS removal (compared to the TKN removal). The pH increased to 9.7, while the nutrient contents (TKN, TP, K) were nearly doubled. Finally, the moisture content increased by 3.7% indicating that the organic matter removal was higher than the evaporation and leaching.

3.5 Cost estimation of full-scale urban pre-composting

Results indicate a mean total potential cost per urban pre-composter of about €11,600 over 10 years for a mass reduction of 33%. The other mass reduction scenarios obtain a mean value of approximately €10,000 – €11,000. Accounting for a 20% variation in the input parameters defined in section **2.4**, it can be seen that for 80% of the cases (i.e. from 10th percentile to the 90th percentile) the total costs will be between about €8,000 and €14,500 at a mass reduction of 33% (**Fig. 4**) and between approximately €7,000 – €14,000 for the other three scenarios. Generally, the majority of this amount is a result of costs savings 50-72% (42-70%), while the remainder is a results of the avoided investment into the conventional collection container. The cost saving are mainly a result of the reduction of gate fees of c.a. 76% (at 33% mass reduction), followed by reduced employment costs for the truck driver which contribute about 13%, reduced initial investment for truck fleet of about 7%, fuel costs 3% and maintenance/insurance of the truck 1%. Since gate fees represent a high share of overall savings, the effect of mass reduction is proportional, with potential cost for a pre-composter reduced between about 3.5% (at 29.7% reduction – 3.7% less reduction) and 10.5% (21.9% mass reduction – 11.5% less reduction). The small differences are a result of monetary savings on transport.

4. Discussion

4.1 Urban pre-composter performance

The results of this study indicate that the urban pre-composter can tackle the typical challenges of composting KW, namely temperature fluctuations (Iyengar and Bhave, 2006), poor oxygen diffusion (Adhikari et al., 2009), excessive moisture content and the related lack of structure (Yang et al., 2013); while also producing a good quality pre-compost.

The combination of forced aeration and agitation tackled the problem of a lack of structure of the KW and provided sufficient oxygen supply. Forced aeration in combination with agitation, also increased removal of water vapor and consequently reduced the waste's moisture content (Pandey, 2003). This was evident in the mass reduction between 22 and $33\%_{FW}$ ($28\text{-}37\%_{TS}$) and volume reductions of 57-62%. These values by far exceed the figures reported in literature when assessing mass and volume reduction (**Table 6**). The best removal performance reported in literature when using solely KW, was a mass reduction of $33\%_{FW}$ ($25\%_{TS}$) achieved in a period of 28 days (Yang et al., 2013). Therefore, in this research, in half of the time a slightly higher wet mass reduction was achieved, while the TS reduction was 11%

higher. Regarding the volume of KW, Nair et al. (2006) achieved a 79-85% reduction in 21 days using tumbler composting bins and with the addition of bulking agents in a ratio 1:4.3 v/v. In the present study a 22% lower volume reduction was achieved in 67% of this time.

It is further crucial that these removal rates where realized without the increase of leachate. The generation of leachate was between 2.1–7.3 mL/kg$_{FM}$, which is lower than in previous reports. Andersen et al. (2011) observed leachate generation of 130 mL/kg$_{FM}$ during a fed-batch composting period of 1 year. In the study of Amlinger et al. (2008) the leachate generated was 270 mL/kg$_{FM}$ when treating source separated organic waste, whereas Wheeler and Parfitt (1999) reported the generation of 31 mL leachate/kg$_{FM}$ when composting a waste mixture composed of 20–30% KW, 60–80% garden waste, and 5% other waste. To put these results into perspective, the worst case scenario of the present study (7.3 mL/kg$_{FM}$) would result in 5.5 L leachate from the full-scale installation (400 PE), whereas the 270 mL/kg$_{FM}$ (Amlinger et al., 2008) are translated into 203 L of leachate. Hence, the forced aeration of the urban pre-composter, in contrast to the passive aeration of the above-mentioned studies, promoted the water vapor removal and thus the minimization of the produced leachate.

Finally, the low pH of the feedstock (4.28-4.96; **Table 3**) retards the transition from mesophilic to thermophilic due to the reduced microbial activity (Sundberg et al., 2004). Indeed Partanen et al. (2010) reported the presence of limited bacterial genera during low pH (i.e. 4.8) composting, dominated by *Acetobacter* and *Lactobacillus*, whereas when the pH increased the microbial populations were more diverse. However, this is an inherent characteristic of KW composting (Sundberg et al., 2004), that is resolved during main composting.

4.2 Main composting

After 54 days of main composting, the overall mass reduction (i.e. pre-composting and main composting) was 61%$_{FW}$ and 69%$_{TS}$ while the volume was reduced by 80%. Similar studies (**Table 6**) have only reported 56.8%$_{TS}$ reductions of 1:3 (in TS) KW:sawdust using force-aerated composting reactors after 65 days (Hwang et al., 2002). This indicates that the combination of pre-composting and main composting results in a 18% higher TS reductions in a comparable time. From the presented data, it can be derived that the pre-composting step had a key contribution to this, as it is responsible for 42%, 48% and 71% of the overall mass, TS and volume reduction in 25% of the time. It can also be derived that 53% of the biodegradable VS (assuming that the remaining 4.09 kg$_{VS}$ after main composting are non-biodegradable) are removed during pre-composting.

4.3 Towards implementing the urban pre-composter

The pre-composting results are promising for full-scale implementation as: (1) The mass and volume of the waste was reduced by up to 33% and 62%, respectively. (2) Low amounts of leachate were produced which were not, as initially planned, used to re-moisten the compost. For the full-scale implementation it is recommended to simply add the leachate to the compost when it is collected. This is feasible due to the low amount of leachate produced, which does increase the moisture content by only 0.82-1.14%. (3) In section **3.2.2** it was concluded that the addition of structure material can be omitted, thereby, avoiding extra costs to supply such structure material. Furthermore, these findings are superior to most processes investigated in literature, of which most studies made use of the addition of bulking agents, in the range of 1:0.8 to 1:3 (in TS) KW:bulking agents (**Table 6**).

Despite the evidence for successful process performance, there are a number of challenges to be addressed for progressing towards implementation in cities, some of which will be outlined here. First and foremost, to be on par between costs for simple community-scale collection and urban pre-composting, future design and optimization work must strive to keep the lifetime costs of 10 years (i.e. OPEX and CAPEX) within specific the economic boundary conditions that are defined by the potential costs of the urban pre-composter (**Fig.4**). It is most likely that these conditions are located in the range between €8,000 and €14,500 as this is representing 80% of the analyzed cases (section 3.5); but if only lower mass removal rates can be realized, for example due to lower temperatures, this range may reduce to €7,000 – 14,000. In addition to this monetary break-even approach, city governments should evaluate benefits that have no direct monetary value such as, reduced environmental impact as a result of fewer km driven (34% reduction i.e. > 50,000 km), less noise and air pollution from traffic and lower odor nuisance to citizens.

A key optimization focus should be on the aeration and stirring frequency. Practice has shown that at least a part of the required electrical energy can be generated from solar panels that are integrated into the housing of the container. The design of the reactor must further address the operation throughout the year and the presents of impurities. Generally, it is expected that the KW composition does not vary significantly over the year (Hanc et al., 2011), while lower winter temperatures could result in lower microbial conversion rates. However, seasonal temperature fluctuations are not expected to significantly affect the underground system, as below 1 meter depth temperature extremes are mitigated (Florides and Kalogirou, 2005). Considering the volume reduction achieved during pre-composting (i.e. 62% for Run 4), the full-scale installation can be three times smaller than currently estimated (3 m^3). Specifically, an 1 m^3 container would cover the needs of 400 PE (including buffer capacity). This implies that current underground space can be used and that there is sufficient space for the necessary equipment. It also implies that the reactor could be designed with sufficient extra capacity to operate for examples at lower temperatures that would require longer collection intervals to realize similar mass reductions.

Another aspect that should be investigated is the effect of impurities such as garden waste; even though the presence of garden waste would likely improve the structure and thus facilitate the composting process. In addition, the effect of the addition of compostable bags should be determined, in order to draw conclusions for the optimal disposal method. Furthermore, odor problems should be investigated. Even though this parameter was not assessed, it is likely that the odor generation is reduced (compared to the scenario of no pre-composting) as a result of the limitation of metabolites of anaerobic degradation (Bidlingmaier and Müsken, 2007). Further optimization of the air outlet pipe, potentially including gas treatment (e.g. biofilter) (Schlegelmilch et al., 2005), could be considered if this found to be necessary.

For implementation of the urban pre-composter in areas that process organic waste through anaerobic digestion, rather than composting, it could also be worthwhile to explore its potential. Taking a look at the results of Run 2, it can be seen that the raw waste initially has 0.33 kg_{VS}/kg_{FM}, while after pre-composting it is equal to 0.25 kg_{VS}/kg_{FM} (**Table 5**). Hence the pre-composted waste contains 22% less biodegradable matter per unit fresh weight, which can be approximated to a 22% lower biochemical methane potential (BMP). However, the mass of the waste is reduced by 33%, thus potentially lowering the gate fee. At the current gate fee for anaerobic digestion of €87 per ton (i.e. the current gate fee of OHW in Belgium; European Commission (2002)), this could result in a new gate fee of €71 per ton[1] or an 18% reduction. Therefore, theoretically there could be an economic advantage of this process, but this should be further investigated with focus on the effect of VS removal on BMP and the actual effect of provision of a new substrate on the gate fee as this will affect by a number of parameters that may change (e.g. lower moisture content, different retention times).

Finally, a follow-up study should also explore the effect of more irregular feeding of the reactor, fluctuations in the KW composition, and potential temperature variations of the underground system, as well as the public acceptance and governance issues that might arise from the application of this system.

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[1] i.e. $New\ Gate\ Fee\ =\ Old\ Gate\ Fee \cdot (1 + BMP\ reduction\ \%) \cdot (1 - Mass\ reduction\ \%)$ or $87\ €/t \cdot (1 + 0.22) \cdot (1 - 0.33)\ =\ 71$

4.4 Compost quality

The maturity of compost is an expression for the degree of completion of the composting process (Bernal et al., 2017). Only a stable compost will have the desired agronomic characteristics, such as appropriate organic matter and nutrient contents. An important parameter to measure the maturity of compost, is the carbon to nitrogen ratio (C/N). As a result of the decomposition of organic material, this ratio will decrease during the process, with values below 20 being acceptable for compost materials, while preferred values are around 15 or lower (Iyengar and Bhave, 2006; Morais and Queda, 2003; VLACO, 2016). Furthermore, the ratio VS/TS constitutes a maturity measure (Andersen et al., 2011). Finally, the quality of compost is defined by chemical properties like pH and N-P-K content.

In the present study, C/N ratios between 19 and 29 were realized after 14 days of pre-composting, which represents a 21-32% reduction. These results are within the range of the values stated in literature. Specifically, Yang et al. (2013) achieved a C/N ratio of 22 after 28 days of composting KW (31% decrease), while for the same period of time Nair and Okamitsu (2010) realized 56% decrease in the C/N ratio when composting 0.43:1 KW:bulking agents, however achieving a notably high final C/N ratio (35) that would require further treatment to reach compost maturity. After main composting a C/N ratio of 12 was realized (overall composting period of 68 days), translating into a 67% decrease and meeting the compost requirements set by the Flemish compost organization (VLACO, 2016). These results compare well to literature. Adhikari et al. (2009) produced a compost with a C/N of 21 after 66 days of composting in a two-stage process, achieving only a 23-54% decrease. In addition, the VS/TS of 0.69 achieved during main composting compares well with other studies where values of 0.45-0.62 were achieved after 365-455 days (Andersen et al., 2011).

Depending on the application, the required pH level of the compost vary between 6-8.5 (Hogg et al., 2002). Therefore, the pH of 9.7 after 68 days of composting is somewhat too high. However, the pH will drop during the curing phase, due to the escape of gaseous NH_3 (Hubbe et al., 2010). While there are no European standards recommended for compost, the Flemish compost organization indicates the average composition of compost derived from vegetable green and fruit waste to be 70% TS, 1.2% TN, 0.13% P (0.6% P_2O_5), and 0.42% K (1% K_2O), in the final product (VLACO, 2016), which is the equivalent of N/P/K content of 1/0.11/0.35. It is evident that further moisture removal is required for the recommended TS contents to be met (currently 27%), as is often the case during the composting of this type of waste (Andersen et al., 2011; Bernal et al., 2017; Iyengar and Bhave, 2006). After the additional moisture removal, the nutrient content of the compost would then reach the values of 2.22 $g_N/g_{product}$, 0.34 $g_P/g_{product}$ and 0.18 $g_K/g_{product}$. These values meet the criteria set by VLACO for N and P content, while given the fact that the K content is a function of the input material, the addition of K is needed. Finally, Partanen et al. (2010) showed that the low pH during composting is interwoven with the prevalence of *Lactobacillus* species. Bacteria belonging to this genus have been reported to produce antibiotic compounds, therefore aiding at the elimination of pathogens potentially present on the feedstock (Partanen et al., 2010).

5 Conclusions

In conclusion, the results for the biological conversions and consequential reduction of mass (22-33%), organics (32-43%), and volume (57-62%) indicate that the concept of urban pre-composting can in principle be operationalized. Similarly, the quality of the pre-compost suggested that residence time at main stage composting can be reduced. The extremely low leachate production (2–7 mL/kg_{FM}) and the potential to completely avoid the addition of structure material are further promising to progress towards implementation, as this will circumvent additional costs and logistical efforts (i.e. dosing of structure material and transport of leachate). From these facts, it can be estimated that construction and 10-year operation/maintenance cost of the pre-composter should be between €8,000 and €14,500. Meeting these economic boundary conditions as well as performing trials under more realistic conditions that include temperature variation, waste composition changes and altered aeration and mixing regimes are crucial to develop the concept of urban pre-composting into a mature and robust technology.

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Table and Figure Captions:

Table 1: Operational parameters of the experimental Runs

Table 2: Assumptions used for the cost calculations including variations for Monte Carlo simulations (variables uniformly distributed; source: OVAM, (2014)). Values with ± indicate the range applied in the Monte Carlo simulations (±20%), the exception to this is the filling percentage. KW: kitchen waste; PE: person equivalent; FTE: full time employment.

Table 3: Characteristics of formulated kitchen waste (FKW), commercially available sawdust, 20:1 (in FW) FKW: sawdust (used in Runs 2-3) and real kitchen waste (RKW) obtained from the collection points. Expressed percentages refer to the fresh (wet) weight ($\%_{FW}$), while the disposal per collection point is expressed in grams per person equivalent (PE) per day

Table 4: Key parameter reductions achieved during pre-composting (14 days), main composting (54 days) period and the combination of pre-composting and main composting (68 days)

Table 5: Compost characteristics after pre-composting (14 days) and main composting period (54 days; overall composting period of 68 days)

Table 6: Comparison of data regarding volume and mass reduction of KW through composting reported in literature.

Fig. 1: Overall design of stationary drum bioreactor with internal agitator: (a) exploded 3D view; (b) front side; (c) side view; (d) two agitator designs used in the experiments.

Fig. 2: Evolution of volume, wet bulk density and dry bulk density in comparison to the amount of loaded material throughout the pre-composting period for Runs 1-4.

Fig. 3: Evolution of volume, wet bulk density and dry bulk density of compost during the main composting period.

Fig. 4: Cumulative distribution function of cost savings of the urban pre-composter implementation over a 10-year period for the four different mass removal efficiencies from Runs 1-4 (i.e. 21.9%, 25.4%, 29.7% and 33.4%). The values represent the net present value of the money saved using urban pre-composting when compared to conventional decentralized kitchen waste collection. The mean value (€11,600) is represented by the vertical line, the grey box represents 80% of the events (i.e. 10-90%).

Table 1: Operational parameters of the experimental Runs

Parameter	Run 1	Run 2	Run 3	Run 4
Kitchen waste (dosage supplied every two days)	Formulated (48 kg=7x6.86 kg)	Formulated (48 kg=7x6.86 kg)	Formulated (48 kg=7x6.86 kg)	Real, from collection points (48 kg=7x6.86 kg)
Additives	-	2.40 kg sawdust (7x0.34 kg)	2.40 kg sawdust (7x0.34 kg); addition of 57.1 mL NaOH 2M/$kg_{\text{waste fed}}$ in every feeding	-
[a]Inoculum	Commercially available compost ($10\%_{FW}$ of mass loaded = 6.86 kg)	[b]Formulated inoculum ($10\%_{FW}$ of mass loaded = 7.20 kg)	[b]Formulated inoculum ($10\%_{FW}$ of mass loaded = 7.20 kg)	[b]Formulated inoculum with adjusted pH ($10\%_{FW}$ of mass loaded = 6.86 kg)
Agitator mixing regime	5 rpm for 5 min: 10 min halt; adjusted on day 3 to 1 rpm for 1 min: 14 min halt	1 rpm for 1 min: 14 min halt	1 rpm for 1 min: 14 min halt	1 rpm for 1 min: 14 min halt
Agitator structure	Straight scraper with internal void	Straight scraper with internal void	Battlemented scraper with internal bars	Battlemented scraper with internal bars
Aeration	1.09-4.37 L_{air}/$kg_{\text{waste added}}$/min	1.04-4.17 L_{air}/$kg_{\text{waste added}}$/min	1.04-4.17 L_{air}/$kg_{\text{waste added}}$/min	1.09-4.37 L_{air}/$kg_{\text{waste added}}$/min
Ambient temperature	17 – 25˚C	21 – 33˚C	21 – 33˚C	21 – 33˚C
Remarks	The initial mixing intensity resulted in waste compaction; problems with leachate exit clogging	Attempt to correct pH by addition of 51.8 mL NaOH 2M/$kg_{\text{waste fed}}$ (on day 10)	-	-

[a]Detailed description of the inoculum preparation can be found in SM

[b]Formulated inoculum contains a part of the pre-compost of the previous run (60% in FW), see SM

Table 2: Assumptions used for the cost calculations including variations for Monte Carlo simulations (variables uniformly distributed; source: OVAM, (2014)). Values with ± indicate the range applied in the Monte Carlo simulations (±20%), the exception to this is the filling percentage. KW: kitchen waste; PE: person equivalent; FTE: full time employment.

Item	Unit	Value
Kitchen waste	t/PE/year	0.05 ± 0.01
Mass reduction[a]	%	21.9; 25.4; 29.7; 33.4
Distance between collection points	km	0.20 ± 0.04
Distance to final disposal point	km	30.8 ± 6.2
Capacity of truck	ton/truck	11.5
Filling percentage of the truck	%	72% ≤ 90% ≤ 100%
Time per emptying (at final discharge point)	min	23.0 ± 4.6
Time to empty sorting street container	min	8.0 ± 1.6
Working year	min/year	99,000 (1,650h)
Average speed travelled between collection points	Km/h	15
Average speed travelled to final discharge point	km/h	40
Truck operation per year	min/year	117,000 (1,950h)
People operating truck	PE/truck	1
Costs	Unit	Value
Fuel costs	euro/km	0.80 ± 0.16
Gate fee composting	euro/ton delivered	Conventional container: 75 ± 15 Urban pre-composter: 56.3 ± 11.3
Employment costs	euro/FTE/year	43,775 ± 8,755
People employed per truck	FTE	1
Cost truck	euro/truck	250,000 ± 50,000
Depreciation time truck	Years	8
Maintenance	euro/truck/year	1,415 ± 283
Insurance truck	euro/truck/year	4,050 ± 810

[a] Values from Run 1-4

Table 3: Characteristics of formulated kitchen waste (FKW), commercially available sawdust, 20:1 (in FW) FKW: sawdust (used in Runs 2-3) and real kitchen waste (RKW) obtained from the collection points. Expressed percentages refer to the fresh (wet) weight ($\%_{FW}$), while the disposal per collection point is expressed in grams per person equivalent (PE) per day

Parameter	FKW (Runs 1,2,3)	RKW (Run 4)	Sawdust (Runs 2,3)	20:1 FKW: sawdust (Runs 2,3)
pH	4.28 ± 0.26	4.96 ± 0.01	6.18 ± 0.02	4.29 ± 0.32
Total solids (TS)	30.9 ± 0.2 %	25.6 ± 0.2 %	93.1 ± 0.2 %	33.8 ± 0.2 %
Volatile solids (VS)	29.8 ± 0.3 %	22.4 ± 1.2 %	92.3 ± 0.5 %	32.8 ± 0.3 %
Fixed solids (FS)	1.08 ± 0.52 %	3.17 ± 1.45 %	0.78 ± 0.59 %	1.07 ± 0.52 %
Moisture content (MC)	69.2 ± 0.2 %	74.4 ± 0.2 %	6.93 ± 0.15 %	66.2 ± 0.2 %
Chemical oxygen demand (COD)	36.8 ± 6.4 %	20.1 ± 0.1 %	52.4 ± 0.0 %	37.5 ± 6.1 %
[a]Organic carbon (OC)	16.3 ± 0.2 %	12.3 ± 0.7 %	50.4 ± 0.2 %	17.9 ± 0.2 %
Total Kjeldahl nitrogen (TKN)	0.52 ± 0.06 %	0.52 ± 0.00 %	0.06 ± 0.00 %	0.50 ± 0.01 %
Total Phosphorus (TP)	0.052 ± 0.005 %	0.071 ± 0.011 %	0.004 ± 0.001 %	0.050 ± 0.001 %
Potassium (K)	0.036 ± 0.001 %	0.048 ± 0.001 %	[b]n/d	0.034 ± 0.001 %
Dry bulk density	172 ± 20 kg_{TS}/m^3	349 ± 5 kg_{TS}/m^3	622 ± 30 kg_{TS}/m^3	196 ± 24 kg_{TS}/m^3
Wet bulk density	559 ± 66 kg_{FW}/m^3	900 ± 18 kg_{FW}/m^3	675 ± 35 kg_{FW}/m^3	567 ± 65 kg_{FW}/m^3
VS/TS	0.97 ± 0.02	0.88 ± 0.06	0.99 ± 0.01	0.97 ± 0.02
[c]Carbon/nitrogen (C/N)	31.5 ± 2.0	25.4 ± 0.1	843 ± 0	36.1 ± 1.9

[a] The organic carbon content (%OC) was calculated using the assumption (%OC)=(%VS)/1.83, as described by Barrington et al. (2002)

[b] not detected

[c] Based on OC and TKN values

Table 4: Key parameter reductions achieved during pre-composting (14 days), main composting (54 days) period and the combination of pre-composting and main composting (68 days)

Parameter		Unit	Pre-compost Run 1	Pre-compost Run 2	Pre-compost Run 3	Pre-compost Run 4	[a]Main composting of pre-compost Run 2	[b]Pre-composting + Main composting
Fresh weight (FW)	Input	kg	53.6	56.4	56.4	52.6	19.5	56.4
	Output	kg	41.8	42.1	39.6	35.0	10.3	22.2
	Reduction	kg	11.7	14.3	16.7	17.6	9.23	34.2
		% of initial	21.9	25.4	29.7	33.4	47.3	60.7
Total Solids (TS)	Initial	kg_{TS}	16.5 ± 0.3	19.3 ± 0.8	19.2 ± 0.5	15.3 ± 0.3	5.95 ± 0.23	19.3 ± 0.8
	Final	kg_{TS}	11.1 ± 0.5	12.8 ± 0.5	12.2 ± 0.8	11.0 ± 0.6	2.76 ± 0.23	5.95 ± 0.1
	Reduction	kg_{TS}	5.34 ± 0.74	6.43 ± 1.32	7.02 ± 1.26	4.28 ± 0.88	3.19 ± 0.47	13.3 ± 0.4
		% of initial	32.4 ± 2.7	33.4 ± 3.2	36.6 ± 3.5	28.0 ± 2.14	53.6 ± 1.6	69.1 ± 6.7
Volatile Solids (VS)	Initial	kg_{VS}	15.6 ± 0.2	18.2 ± 0.8	18.1 ± 0.4	11.8 ± 0.7	4.96 ± 0.15	18.2 ± 0.8
	Final	kg_{VS}	10.2 ± 0.2	10.7 ± 0.6	10.3 ± 0.7	8.07 ± 0.27	1.90 ± 0.20	4.09 ± 0.16
	Reduction	kg_{VS}	5.44 ± 1.16	7.55 ± 1.41	7.85 ± 1.03	3.72 ± 1.01	3.06 ± 0.48	14.1 ± 0.3
		% of initial	34.9 ± 2.7	41.4 ± 3.8	43.3 ± 3.9	31.5 ± 1.9	61.7 ± 1.5	77.6 ± 7.1
	Removal rate	$kg_{VS}/m_{reactor}^3$/day	1.94 ± 0.41	2.70 ± 0.50	2.80 ± 0.37	1.33 ± 0.36	1.42 ± 0.17	1.68 ± 0.07
Moisture	Initial	kg_{H2O}	38.2 ± 0.3	37.2 ± 0.8	37.8 ± 3.2	38.1 ± 0.31	13.6 ± 0.2	37.2 ± 0.8
	Final	kg_{H2O}	30.7 ± 0.5	29.3 ± 0.5	27.5 ± 0.8	24.1 ± 0.6	7.54 ± 0.23	16.3 ± 0.1
	Reduction	kg_{H2O}	7.48 ± 0.74	7.91 ± 1.32	10.4 ± 4.0	14.0 ± 0.9	6.04 ± 0.47	20.9 ± 0.2
		% of initial	19.6 ± 3.7	21.3 ± 4.0	27.4 ± 5.2	36.8 ± 7.0	44.5 ± 3.0	56.3 ± 10.5
Volume	Initial	L	95.9	101	101	84.8	21.6	101
	Final	L	41.4	43.9	41.4	32.6	10.1	20.5
	Reduction	L	54.5	57.2	59.5	52.2	11.5	80.5
		% of initial	56.8	56.6	59.0	61.6	53.2	79.7

[a]Input waste: pre-compost of Run 2; only the results of maturation phase are presented (54 days)

[b]Input waste: pre-compost of Run 2; the combined effect of pre-composting and maturation phase is calculated for Run 2

Table 5: Compost characteristics after pre-composting (14 days) and main composting period (54 days; overall composting period of 68 days)

Parameter	Unit	Run 1		Run 2		Run 3		Run 4		Run 2
		[a]Input waste	Pre-compost	[b]Input waste	Pre-compost	[b]Input waste	Pre-compost	[c]Input waste	Pre-compost	Matured pre-compost
pH	-	4.28 ± 0.26	3.77	4.29 ± 0.32	4.11	[d]7.48 ± 0.08	4.03	4.96 ± 0.01	4.22	9.7
Total Solids (TS)	$\%g_{TS}/g_{FW}$	30.9 ± 0.2	26.6 ± 1.2	33.8 ± 0.2	30.5 ± 1.2	33.8 ± 0.2	30.7 ± 1.9	25.6 ± 0.2	31.2 ± 1.6	26.8 ± 2.3
Volatile Solids (VS)	$\%g_{VS}/g_{FW}$	29.8 ± 0.3	24.3 ± 2.3	32.8 ± 0.3	25.4 ± 1.4	32.8 ± 0.3	25.9 ± 1.7	22.4 ± 1.2	23.0 ± 1.1	18.4 ± 1.9
Fixed Solids (FS)	$\%g_{FS}/g_{FW}$	1.08 ± 0.52	2.33 ± 3.45	1.07 ± 0.52	5.09 ± 2.6	1.07 ± 0.52	4.79 ± 3.66	3.17 ± 1.45	8.18 ± 2.85	8.38 ± 4.16
Moisture content (MC)	$\%g_{H2O}/g_{FW}$	69.2 ± 0.2	73.4 ± 1.2	66.2 ± 0.2	69.5 ± 2.6	66.2 ± 0.2	69.3 ± 1.9	74.4 ± 0.2	68.8 ± 1.8	73.2 ± 2.3
Chemical Oxygen Demand (COD)	$\%g_{COD}/g_{FW}$	36.9 ± 6.4	20.4 ± 0.3	37.5 ± 6.1	22.8 ± 0.3	37.5 ± 6.1	24.7 ± 0.1	20.1 ± 0.1	24.2 ± 0.2	13.9 ± 0.2
[e]Organic Carbon (OC)	$\%g_{OC}/g_{FW}$	16.3 ± 0.2	13.3 ± 1.3	17.9 ± 0.2	13.9 ± 0.8	17.9 ± 0.2	14.2 ± 0.2	12.3 ± 0.7	12.9 ± 0.4	10.1 ± 1.0
Total Kjeldahl Nitrogen (TKN)	$\%g_{TKN}/g_{FW}$	0.52 ± 0.06	0.57 ± 0.00	0.50 ± 0.01	0.48 ± 0.00	0.50 ± 0.01	0.49 ± 0.00	0.52 ± 0.00	0.69 ± 0.01	0.85 ± 0.01
Total Phosphorus (TP)	$\%g_{TP}/g_{FW}$	0.052 ± 0.005	0.047 ± 0.004	0.050 ± 0.001	0.068 ± 0.000	0.050 ± 0.001	0.076 ± 0.003	0.071 ± 0.011	0.100 ± 0.01	0.125 ± 0.001
Potassium (K)	$\%g_{K}/g_{FW}$	0.036 ± 0.001	0.046 ± 0.001	0.034 ± 0.001	0.044 ± 0.001	0.034 ± 0.001	0.046 ± 0.002	0.048 ± 0.001	0.067 ± 0.001	0.071 ± 0.000
Dry bulk density	kg_{TS}/m^3	172 ± 20	269 ± 2	196 ± 24	294 ± 3	196 ± 24	313 ± 2	349 ± 5	377 ± 4	200 ± 3
Wet bulk density	kg_{FW}/m^3	559 ± 66	996 ± 37	567 ± 65.4	963 ± 10	567 ± 65.4	957 ± 5	900 ± 18	1073 ± 10	707 ± 13
TKN/VS	-	0.017 ± 0.125	0.023 ± 0.096	0.015 ± 0.029	0.019 ± 0.057	0.015 ± 0.029	0.019 ± 0.070	0.023 ± 0.057	0.030 ± 0.062	0.046 ± 0.115
[f]C/N	-	31.5 ± 2.0	23.4 ± 0.1	36.1 ± 0.2	24.5 ± 0.1	36.1 ± 0.2	28.7 ± 0.0	25.4 ± 0.1	18.8 ± 0.0	11.8 ± 0.1

[a] 100% FKW

[b] 20:1 (in FW) FKW: sawdust

[c] 100% RKW

[d] The pH of the waste was adjusted through the addition of NaOH 2M on the sawdust. The sawdust was subsequently dried to achieve the initial moisture content.

[e] The organic carbon content (%OC) was calculated using the assumption (%OC)=(%VS)/1.83, as described by Barrington et al. (2002)

[f] Based on OC and TKN values

Table 6: Comparison of data regarding volume and mass reduction of KW through composting reported in literature.

Composting reactor	Aeration (L_{air}/min)	Mixing type/ frequency	Feeding regime/ frequency/ loading rate	Composting material	Reactor volume (L)	Composting time (days)	Composting temperature (˚C)	Volume reduction (%)	Mass reduction (%)	Reference
pile at composting chambers	n/a	Manual turning/0-3 times per week	batch/-/-	KW^a	2100	n/a	25-64	60	n/a	Mbuligwe et al., 2002
air-tight, stainless steel digesters	0.15-0.3	n/a	batch/-/-	1:1:1 (TS) mixed paper: yard waste: KW^b	25	47	n/a	n/a	$58.4\%_{TS}$	Komilis and Ham, 2003
tumbler composting bins	n/a	n/a	batch/-/-	3:1.25:1 (v/v) grass clippings: shredded paper: KW^c	n/a	21	25-60	79-85	n/a	Nair et al., 2006
horizontal vessel composter; cylindrical vessel composter	passive	n/a	batch/-/-	1:1.5 (TS) KW^d: chopped wheat straw	70.7; 30.5	10 days in vessel; 56 days of maturation	20-<50	n/a	$39\%_{TS}$ ($77\%_{FW}$)	Adhikari et al., 2009
				1.2:1 (TS) KW^d: chopped wheat straw			19-<50	n/a	$68\%_{TS}$ ($86\%_{FW}$)	
				1.12:1 (TS) KW^d: chopped hay			18-50	n/a	$52\%_{TS}$ ($84\%_{FW}$)	
				1.14:1 (TS) KW^d: pine wood shavings			19-37	n/a	$50\%_{TS}$ ($71\%_{FW}$)	
compost barrels	passive	barrels were rolled/ 10 times per day	batch/-/-	7.5:4:1:5:7.5 compost: sawdust: paper/cardboard : grass clippings: KW^e	230	28	25-55	44.7*	n/a	Nair and Okamitsu, 2010
insulated cylindrical vessels	*4.4-5.2 (30 min); 30 min halt	yes/ turned weekly	batch/-/-	5.7:1 (FW) KW^f: cornstalks	60	28	71	n/a	$25.5\%_{TS}$ ($28.1\%_{FW}$)	Yang et al., 2013
				5.7:1 (FW) KW^f: sawdust			75	n/a	$35.8\%_{TS}$ ($37.5\%_{FW}$)	
				5.7:1 (FW) KW^f: spent mushroom substrate			79	n/a	$24.8\%_{TS}$ ($25.9\%_{FW}$)	
				KW^f			Around 65	n/a	$24.8\%_{TS}$ ($33.2\%_{FW}$)	
on-site composting reactor	15	horizontal agitator/ 0.25 rpm	fed-batch/daily/1 kg_{waste}/day	1:3 (TS) KW^g: sawdust	30	65	35-50	n/a	$56.8\%_{TS}$*	Hwang et al., 2002
complete mix reactor	passive	yes/ n/a	fed-batch; batch/daily (4 weeks); no feeding (4 weeks)/ 0.5 kg_{waste}/day (2 weeks); 1 kg_{waste}/day (2 weeks); batch (4 weeks)	KW^h	n/a	60	24-43	91.9 - 92.3	n/a	Iyengar and Bhave, 2006
facultative reactor	passive	no/-					23-41	81.6-83.5	n/a	
	passive	no/-	fed-batch/weekly/	separated OHW^i	800	84	0-70	n/a	$57\%_{FW}$	

			0.4-6.7 kg$_{waste}$/day							
heap at wooden composters			fed-batch/weekly/ 0.8-7.5 kg$_{waste}$/day			357		n/a	59%$_{FW}$	Amlinger et al., 2008
windrow composting		mechanical turning/ 1-2 times per week	fed-batch/1-2 times per week/ 87.1 kg$_{waste}$/day		-	67	0-75	n/a	45%$_{FW}$	
			fed-batch/1-2 times per week/ 69.7 kg$_{waste}$/day			76		n/a	53%$_{FW}$	
cone-shaped home composter	passive	manual mixing/ weekly	fed-batch; batch/weekly (3 months); batch (3 months)/ 0.40-0.52 kg$_{waste}$/day	OHW[j]	320	365	0-28	n/a	*60.3%$_{TS}$ (55.0%$_{FW}$)	Andersen et al., 2011
									*61.2%$_{TS}$ (65.0%$_{FW}$)	
		manual mixing/ once every 6 weeks							*59.6%$_{TS}$ (64.0%$_{FW}$)	
			fed-batch; batch/weekly (6 months); batch (3 months)/ 0.40-0.52 kg$_{waste}$/day			455			*62.7%$_{TS}$ (73.0%$_{FW}$)	
		no/-							*60.3%$_{TS}$ (56.0%$_{FW}$)	
			fed-batch; batch/weekly (3 months); batch (3 months)/ 0.40-0.52 kg$_{waste}$/day			365			*56.0%$_{TS}$ (65.0%$_{FW}$)	
passive aeration composting bins	passive	no/-	fed-batch; batch/daily (roughly 28 days); batch (120 days)/ 1.6 kg$_{waste}$/day	1:0.28 (FW) KW[k]: dry leaves	200	120	24-55	n/a	40.3 – 61.5%$_{TS}$	Karnchanawong and Suriyanon, 2011

TS = total solids; FW = fresh weight

*calculated from data

[a]orange peels and remains (45%$_{FW}$); banana peels (35%$_{FW}$); cassava-potato peel (8%$_{FW}$); vegetable remains (5%$_{FW}$); food leftovers (4%$_{FW}$); remains of onions, tomatoes and carrots (3%$_{FW}$)

[b]mixture of cooked pasta, cooked meat, lettuce, potatoes and carrots

[c]lettuce, cabbage, oranges, tomatoes, mandarins, pears, apples and broccoli

[d]raw and cooked vegetable and fruit residues

[e]vegetable scraps, coffee grinds and food leftovers (not specified if composition is presented in %$_{FW}$ or %$_{v/v}$)

[f]vegetables (41.6%$_{FW}$); peels (29.7%$_{FW}$); staple food (22.3%$_{FW}$); meat (0.2%$_{FW}$); eggshells, bones, and shells (4.0%$_{FW}$); nutshells and cores (2.2%$_{FW}$)

[g]rice (39%$_{FW}$); vegetables (31%$_{FW}$); wheat flour (24%$_{FW}$); meat (4%$_{FW}$) and fish (2%$_{FW}$)

[h]raw vegetable and cooked food

[i]composition not specified

[j]KW, small amounts of flowers and soil from the household

[k]50%$_{FW}$ discarded during preparation (mainly vegetables); 50%$_{FW}$ leftover food (mainly rice and noodles)

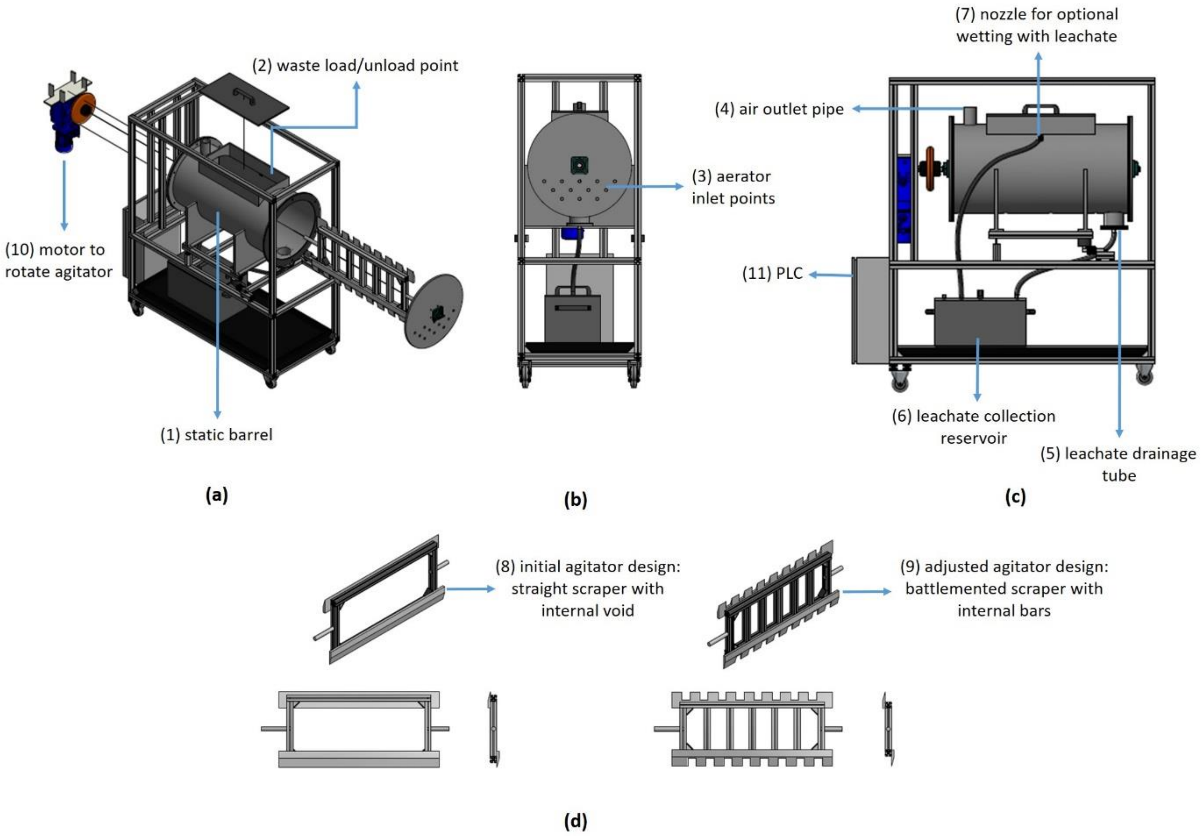
(7) nozzle for optional wetting with leachate
(2) waste load/unload point
(4) air outlet pipe
(3) aerator inlet points
(10) motor to rotate agitator
(11) PLC
(6) leachate collection reservoir
(1) static barrel
(5) leachate drainage tube
(a)
(b)
(c)
(8) initial agitator design: straight scraper with internal void
(9) adjusted agitator design: battlemented scraper with internal bars
(d)

Fig. 1

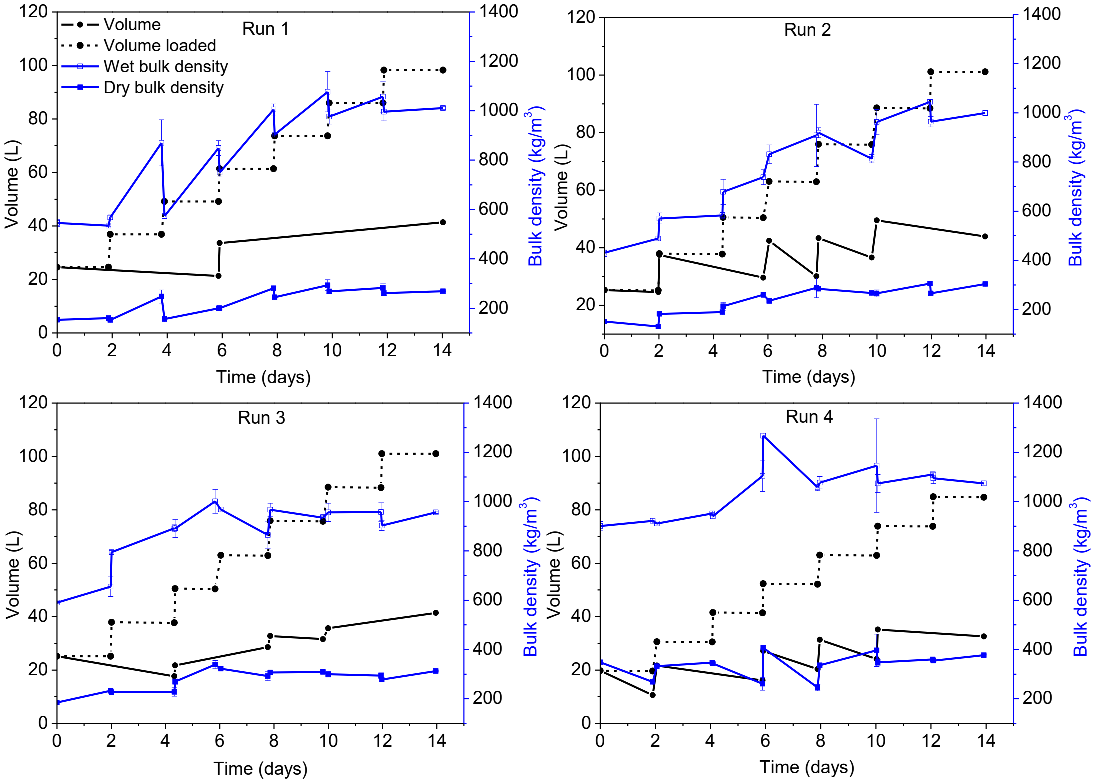
Run 1
Run 2
Run 3
Run 4
Volume
Volume loaded
Wet bulk density
Dry bulk density
Volume (L)
Bulk density (kg/m^3)
Time (days)
0
20
40
60
80
100
120
200
400
600
800
1000
1200
1400
0
2
4
6
8
10
12
14

Fig. 2

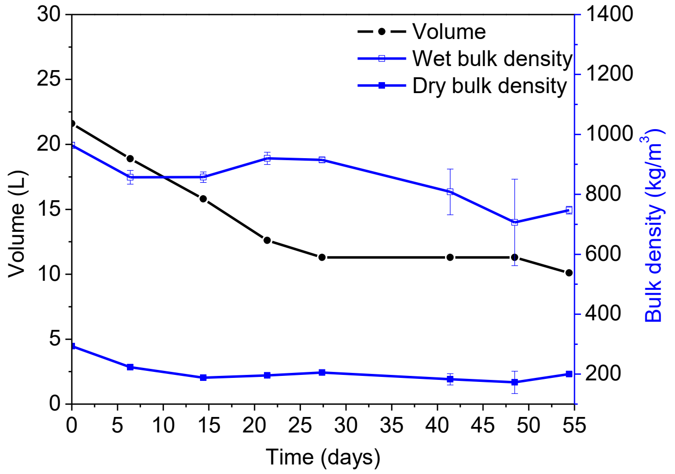
Volume
Wet bulk density
Dry bulk density
Volume (L)
Bulk density (kg/m3)
Time (days)
0
5
10
15
20
25
30
35
40
45
50
55
200
400
600
800
1000
1200
1400

Fig. 3

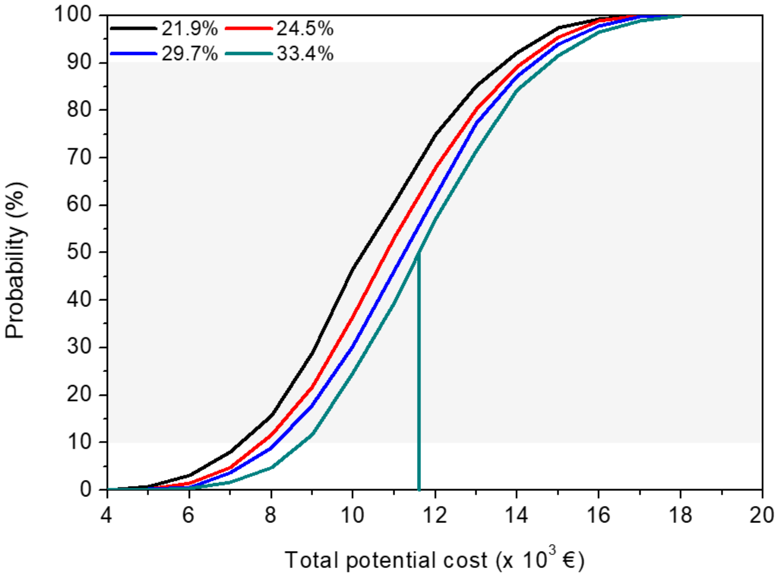
21.9%
24.5%
29.7%
33.4%
Probability (%)
0
10
20
30
40
50
60
70
80
90
100
4
6
8
10
12
14
16
18
20
Total potential cost (x 10^3 €)

Fig. 4

SUPPLEMENTARY MATERIAL

Proof of concept of high-rate decentralized pre-composting of kitchen waste: optimizing design and operation of a novel drum reactor

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Number of pages: 13

Number of figures: 3

Number of tables: 3

1. High moisture content and lack of structure hinders composting of kitchen waste

It is often stated that kitchen waste constitutes an unfavorable feeding material for composting due to the high moisture content and lack of structure (Amlinger et al., 2008; Andersen et al., 2011; Hwang et al., 2002; Iyengar and Bhave, 2006; Karnchanawong and Suriyanon, 2011; Komilis and Ham, 2003; Mbuligwe et al., 2002; Nair et al., 2006; Nair and Okamitsu, 2010; Yang et al., 2013). A crucial factor for composting is moisture content. When low values are presented the biological processes are hindered and thus the produced compost is immature, while high moisture content results in compacted solid material that reduces the air permeability, creating anaerobic zones (Shen et al., 2015). Nevertheless, there is a critical threshold of <46%, below which the microbial activity stops (Hwang et al., 2002). Hence, special attention should be paid to this parameter, especially when composting KW, due to the high moisture content of the feedstock (Amlinger et al., 2008; Andersen et al., 2011; Hwang et al., 2002; Iyengar and Bhave, 2006; Karnchanawong and Suriyanon, 2011; Komilis and Ham, 2003; Mbuligwe et al., 2002; Nair et al., 2006; Nair and Okamitsu, 2010; Papadopoulos et al., 2009; Shen et al., 2015; Yang et al., 2013), which lowers the effectiveness of the process (Yang et al., 2013). The moisture content range reported in the reviewed studies is between 67 and 85%. In particular, fruits in the KW contribute the highest share to the liquid fraction with 80-88% moisture content (Adhikari et al., 2009; Nair et al., 2006) also resulting a rather amorphous waste mixture with a lack of structure.

Therefore, it is common to use bulking agents or structure material to provide structure and porosity to the solid mixture. It increases the aeration efficiency and offers the advantages of initially decreasing the moisture content and preventing the uncontrolled moisture reduction through absorbing a part of the leachate generated (Adhikari et al., 2009; Hwang et al., 2002; Karnchanawong and Suriyanon, 2011; Komilis and Ham, 2003; Nair et al., 2006; Nair and Okamitsu, 2010; Yang et al., 2013). The latter aids in maintaining the microbial activity at high levels. The lack of structure and porosity does often lead to the addition of bulking material in order to increase the penetration of air (Adhikari et al., 2009; Hwang et al., 2002; Karnchanawong and Suriyanon, 2011; Komilis and Ham, 2003; Nair et al., 2006; Nair and Okamitsu, 2010; Yang et al., 2013), but there is an evident need to carefully select the bulking agents in order to minimize the costs of purchasing and transportation (Adhikari et al., 2009).

2. Materials and Methods

2.1 Inoculum preparation

All inoculums used were prepared one week before the initiation of the experiments. They were mixed daily and were maintained at 27 ± 2˚C. The inoculum used in Run 1 consisted of commercially available compost, while for Runs 2-4 it was formulated using 3 components: commercially available compost; a part of the pre-compost from the previous Run and commercially available liquid cultures of heterotrophic bacteria on a ratio of 33:60:7 (in FW). The latter, apart from a source of heterotrophic microbes, was also used in order to regulate the MC at levels between 60 and 65%. The pH of the inoculum used in Runs 3 and 4 was regulated at 7.0-7.5 using NaOH 2M. The inoculum was provided at a ratio of inoculum to substrate 1:1 (in FW) at the initiation of the experiment.

2.2 Real kitchen waste composition

More specifically, vegetable, garden and fruit waste (VGF) was obtained from the city of Antwerp. The waste was composed of vegetables (mainly potatoes and carrots; smaller amounts of cabbage, broccoli, tomato, lettuce, paprika, celery, pumpkin), fruit (mainly oranges, apples, bananas; smaller amounts of pears, pineapple, grapes) cooked food (pasta, lasagna, noodles), bread, raw meat, waffles, spent coffee grounds and smaller amounts of dairy products.

2.3 Reactor design

The reactor configuration is illustrated in **Fig. 1**.

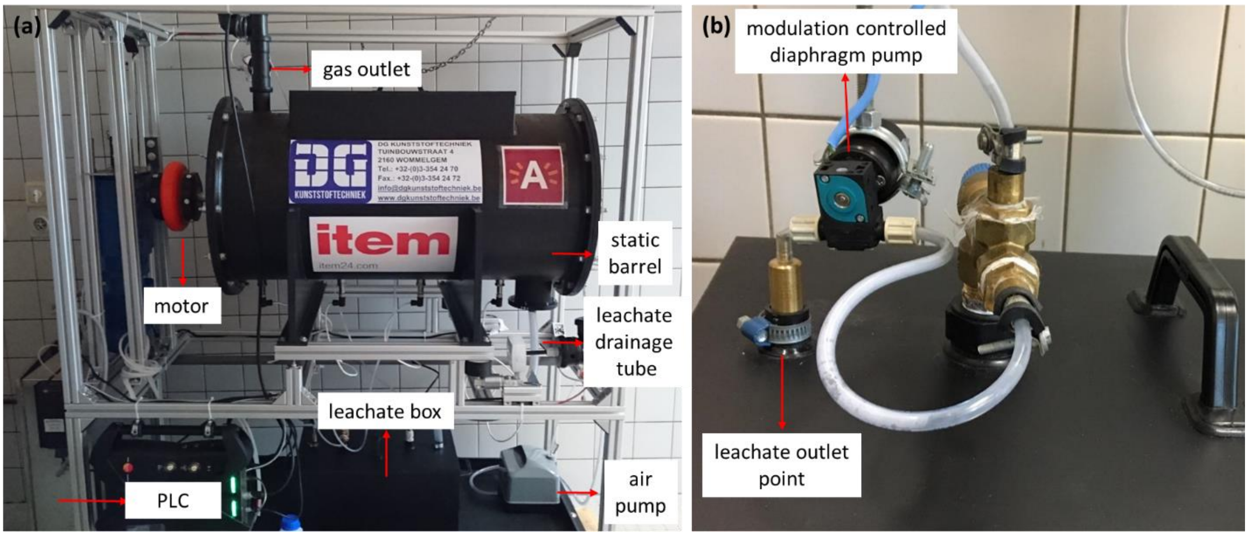

Fig. 1: Pictures of (a) the Urban pre-composted reactor and (b) the leachate recirculation apparatus.

2.4 Analytical techniques

The measurements of total suspended solids (TSS), volatile suspended solids (VSS), total solids (TS), volatile solids (VS), moisture content, biochemical oxygen demand (BOD) and acidity were conducted according to “Standard Methods for the Examination of Water and Wastewater” (APHA et al., 2012). The determination of bulk density was performed using the method ASTM E1109-86 (ASTM, 2009). The pH was determined using edge® Multiparameter pH-meter with HI12300 Digital PEI Body pH electrode, while the pH of the solid waste was measured through the method USEPA 9045D (US EPA, 2004). Electric conductivity (EC) analysis was performed using edge® Multiparameter EC/TDS/Salinity meter equipped with HI763100 Digital EC/Temperature electrode. Chemical oxygen demand (COD), total phosphorus (TP) and potassium (K) content were determined using commercially available test kits (COD Cell Test, Phosphate Cell Test and Potassium Cell Test Merck KGaA, Darmstadt, Germany, respectively). Solid samples for COD and TKN measurement were dried at

70˚C overnight in order to avoid alteration in their physicochemical characteristics. Finally, NH_4 and NO_3^- determination was performed using a Skalar San^{++} Continuous Flow Analyzer (Skalar Analytical B.V). All analyses were performed in triplicate and mean values are presented.

2.5 Monte Carlo simulation

The Monte Carlo simulations were implemented in excel using a the RANDBETWEEN function for the 20% variation around a base value. The 1,000 scenarios in the Monte Carlo were run using the data table function in Excel. Data were then plotted in a cumulative frequency distribution.

The net present value (NPV) was calculated for all annual cash flows (discount rate 5%) (equation 1). This is, all incurred costs with exception of the investment into trucks and the conventional container for KW collection. These investment costs, were instead added to the first set of costs without discounting as they are incurred in year zero. For trucks, cost savings were estimated based one the time saved for collection, given an annual operational time of 117,000 minutes (1,950 h). This resulted in c.a. 3 trucks less than in the initial situation. Similarly, the costs for the conventional containers have been added to the overall cost savings as a last step to determine the potential costs of the urban pre-composter.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1-i)^t} - initial\ investment \tag{1}$$

where t is the year of the cash flow, n is all years considered (i.e. 10) and R is the cash flow.

3. Results

3.1 Composting process performance

3.1.1 Mass reduction

Fig.3 Illustrates the evolution of total mass, moisture, volatile solids (VS) and fixed solids (FS) and in comparison to the amount of loaded material throughout the experimental period.

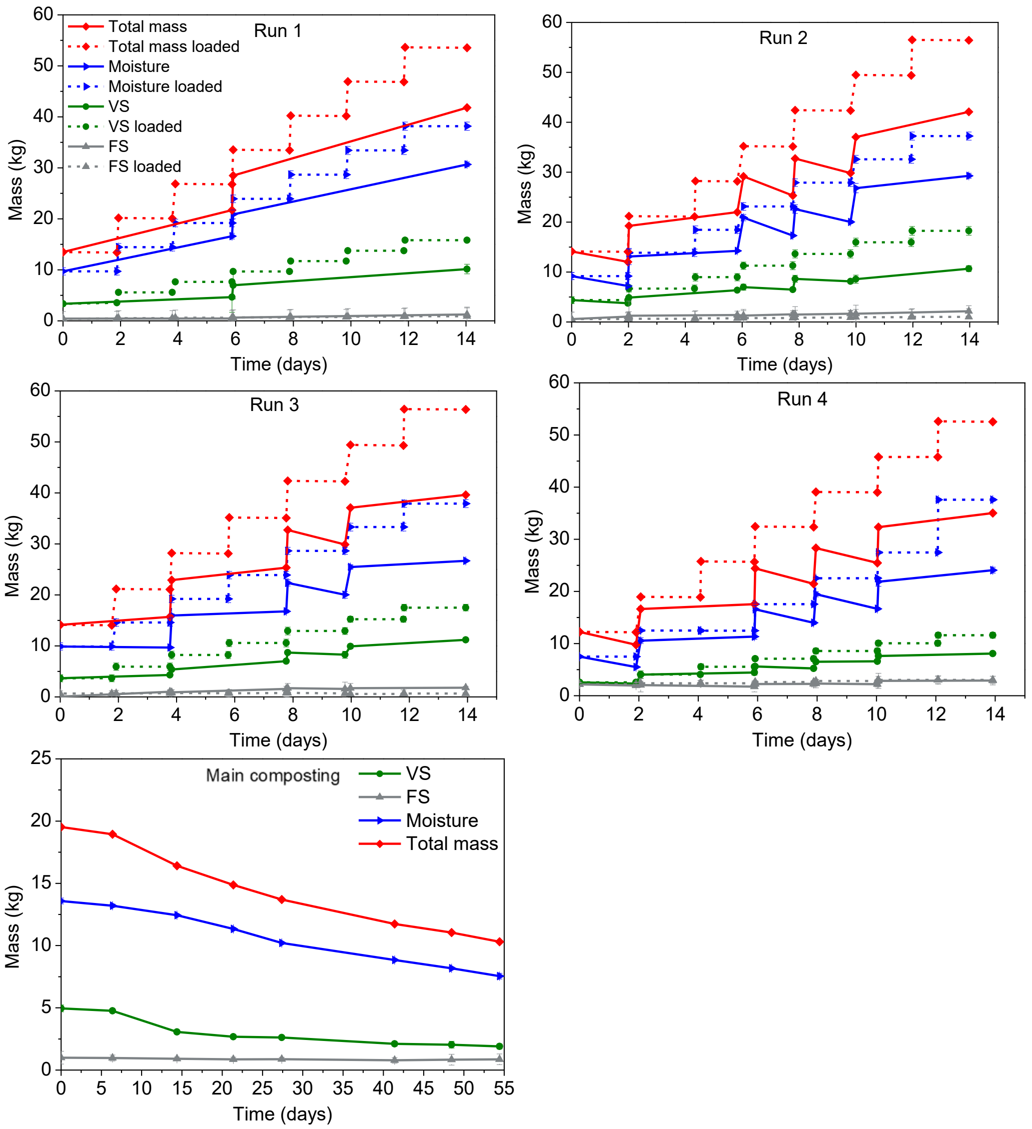

Fig. 3: Evolution of total mass, moisture, volatile solids (VS) and fixed solids (FS) in comparison to the amount of loaded material throughout the pre-composting period for Runs 1-4 and main composting.

3.1.2 COD ant TKN evolution

The COD removal rates presented different pattern for Runs 2-3, with Run 2 presenting the highest value (3.7 $kg_{COD}/m_{reactor}^3/day$) possibly due to the addition of base during the 10th day of the experiment, which resulted in higher COD solubilization and leaching. The lowest rate was again presented when pre-composting RKW, as a result of the lower initial amount of COD in this case. Finally, when comparing the rates for pre-composting and main composing (**Table 1**) it can be seen that 47% and 62% higher rates were achieved with the urban pre-composter for VS and COD removal, respectively.

Table 1: COD and TKN reductions achieved during pre-composting (14 days), main composting (54 days) period and the combination of pre-composting and main composting (68 days)

Parameter		**Unit**	**Pre-compost Run 1**	**Pre-compost Run 2**	**Pre-compost Run 3**	**Pre-compost Run 4**	**[a]Main compost of pre-compost Run 2**	**[b]Pre-composting + Main composting**
Chemical Oxygen Demand (COD)	**Initial**	kg_{COD}	18.8 ± 0.0	20.1 ± 0.1	17.8 ± 0.0	10.7 ± 0.1	4.46 ± 0.06	20.1 ± 0.1
	Final	kg_{COD}	10.9 ± 0.2	9.61 ± 0.14	9.80 ± 0.03	8.46 ± 0.1	1.43 ± 0.02	3.08 ± 0.03
	Reduction	kg_{COD}	7.84 ± 0.21	10.4 ± 0.21	7.98 ± 0.06	2.27 ± 0.08	3.03 ± 0.08	17.0 ± 0.1
		% of initial	41.7 ± 3.9	52.1 ± 5.2	44.9 ± 4.0	21.2 ± 1.1	67.9 ± 1.5	84.6 ± 8.5
	Removal rate	$kg_{COD}/m_{reactor}^3/day$	2.80 ± 0.08	3.73 ± 0.08	2.85 ± 0.02	0.81 ± 0.03	1.40 ± 0.03	1.88 ± 0.01
Total Kjeldahl Nitrogen (TKN)	**Initial**	kg_{TKN}	0.27 ± 0.00	0.29 ± 0.01	0.28 ± 0.09	0.28 ± 0.00	94.4 ± 1.0	0.29 ± 0.01
	Final	kg_{TKN}	0.24 ± 0.00	0.20 ± 0.00	0.23 ± 0.00	0.24 ± 0.00	87.5 ± 1.2	0.19 ± 0.02
	Reduction	kg_{TKN}	0.03 ± 0.00	0.09 ± 0.01	0.06 ± 0.10	0.04 ± 0.00	6.90 ± 2.191	0.10 ± 0.42
		% of initial	11.3 ± 0.0	29.9 ± 0.0	20.2 ± 0.0	13.1 ± 0.0	7.31 ± 3.45	35.1 ± 0.1

3.1.3 Volume reduction and bulk density increase

Table 2 illustrates the changes in bulk density.

Table 2. Wet and dry bulk density increase during Runs 1-4.

	Wet bulk density increase (%)	**Dry bulk density increase (%)**
Run 1	85.4 ± 3.3	76.1 ± 3.3
Run 2	124 ± 5	94.6 ± 5
Run 3	90.9 ± 4	101 ± 4
Run 4	19.2 ± 3.0	8.23 ± 3.04

3.1.4 pH

The results of this study did not show any relation between the initial pH and final pH during the short period of pre-composting. Remarkably, the pH of the input waste during Run 3 was set at c.a. 7.5 with the addition of base, and this resulted in pre-composted waste with pH 4.0, while the respective values during Run 4 (no pH control) were 5.0 and 4.2. This is expected due to the formation of organic acids at this early composting stage. In the following stages of composting, the pH increased due to the consumption of acidic organic compounds as well as the escape of NH_3 (Bernal et al., 2017).

Futhermore, during Run 2, pH presented some fluctuations after each feeding for the first 6 days. Specifically, the use of formulated inoculum and sawdust resulted in an initial pH value of 5.89. This value remained stable for the first 2 days and dropped to around 5.0 after the feedings on days 2 and 4. These drops were ascribed to the sampling approach after the feeding (the substrate needs some time to homogenize in the reactor), which was improved in the next experiments. On day 10, the substrate was supplemented with base (**Fig. 3**) which did not aid in the minimization of the pH drop.

3.1.5 Temperature

The temperature of the system was found to be related to the ambient temperature, with the temperatures achieved never being higher than 2-5°C than the ambient. More specifically, all the temperature drops observed in **Fig. 3** represent periods that the ambient temperature dropped.

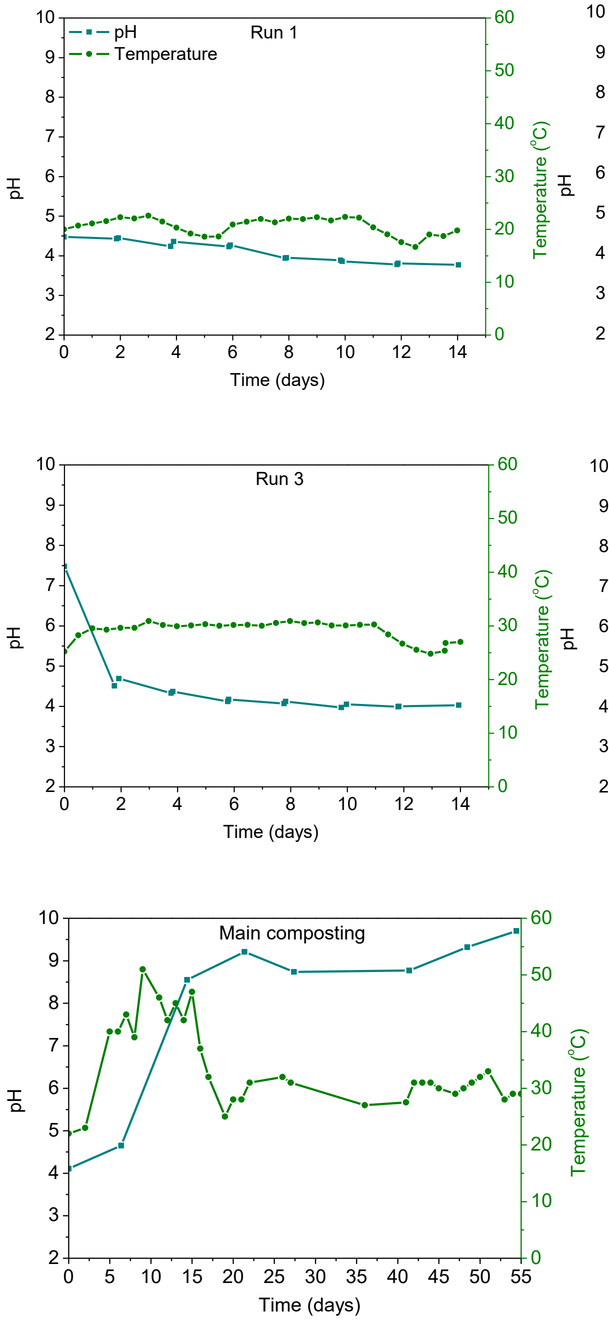

Fig. 3: Evolution of pH and temperature throughout the composting period for Runs 1-4 and main composting.

3.2 Leachate characteristics

Table 2 summarizes the characteristics of the leachate generated in each Run. The total leachate produced amounted 115, 205, 207 and 384 mL, which correspond to 2.1-7.3 mL/kg$_{FM}$. The pH was between 4.3 and 6.4, with the higher values presented in Runs 3-4 as a result of the more effective aeration achieved from the new agitator design.

The leachate was characterized by high concentrations of nutrients and organic compounds. The TSS content presented lower value in Run 1 (2.9 g/L), while in the Runs 2-4 it ranged between 9.1-13 g/L. The VSS content presented similar values in Runs 2-4 (7.4-7.8 g/L), with similar value to TSS presented in Run 1 (2.5 g/L). The BOD_5/COD ratio was 0.38, 0.29, 0.61, 0.65 for Runs 1-4, indicating the higher biodegradable compound leaching in the last two runs. COD/TKN were 83, 43, 31, 59 for Runs 1-4 (the respective values of solid waste were 71, 76, 76 and 42), showing that when sawdust was used (Runs 2-3) the COD leaching was lower in comparison to the TKN leaching, probably due to absorbance of soluble COD. It should be noted that the higher COD leaching in Run 2 (compared to Run 3) was attributed to the higher COD solubilization in the waste, as discussed earlier. The higher organic and nutrient load was present in Run 4, possibly due to the highest decomposition extent of RKW that allowed more nutrient leaching. The lower concentrations observed in Run 1 are ascribed to the lower solid waste decomposition extent, whereas the higher values in Runs 2-4 are attributed to the higher solid waste degradation. It is worth noticing that the leachate produced from this type of waste is characterized by markedly high K content and salinity levels which are attributed to the nature of the KW. In the present study, the K concentration was 579-1619 mg_K/L and the EC presented values up to 31 mS/cm. In all cases ammonium was detected in the leachate, with H_4^+/TKN presenting values of 0.04 for Runs 1-2, 0.15 for Run 3 and 0.42 for Run 4. The higher values in Runs 3-4 indicate a greater organic nitrogen hydrolysis extent while the value for Run 4 also indicates the greater decomposition extent of RKW at the time of the initiation of the composting process. Interestingly, in Run 3 small amounts of nitrate were detected (4.5 mg_N/L), while this was not the case for the rest of the runs. This is attributed to the fact that the leachate produced in Run 3 was characterized by a pH value (> pH 6) that can sustain the process of nitrification (Villaverde et al., 1997). Even though the pH was suitable in Run 4, nitrate was not detected as the ammonium levels reached inhibiting values (Hopkinson and Giblin, 2008).

Table 3: Leachate characteristics at the end of each Run (14 days)

Parameter	**Unit**	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Quantity	mL/kg_{FM}	2.10	3.63	3.67	7.31
pH	-	4.28	4.29	6.21	6.43
Electrical conductivity (EC)	mS/cm	5.38	24.48	30.9	30.2
Total Suspended Solids (TSS)	g_{TSS}/L	2.90 ± 0.31	9.14 ± 0.85	10.9 ± 0.2	12.5 ± 0.2
Volatile Suspended Solids (VSS)	g_{VSS}/L	2.53 ± 0.25	7.6 ± 0.7	7.44 ± 0.20	7.82 ± 0.20
Chemical Oxygen Demand (COD)	g_{O2}/L	48.7 ± 2.2	81.7 ± 0.3	65.5 ± 0.3	235 ± 3
Biochemical Oxygen Demand (BOD_5)	g_{O2}/L	18.3 ± 1.7	54.8 ± 1.5	39.8 ± 2.3	152 ± 3
Total Kjeldahl Nitrogen (TKN)	mg_N/L	587 ± 17	1921 ± 17	2090 ± 13	4002 ± 105
Ammonium (NH_4^+)	mg_N/L	25.4 ± 0.0	83.0 ± 0.7	322 ± 0	1685 ± 10
Nitrate (NO_3^-)	mg_N/L	[a]n/d	[a]n/d	4.49 ± 0.69	[a]n/d
Total phosphorus (TP)	mg_P/L	228 ± 8	569 ± 12	459 ± 17	107 ± 3
Potassium (K)	mg_K/L	579 ± 3	1371 ± 95	958 ± 26	1619 ± 9

[a]not detected

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