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Abstract: Rather than landfilling, composting the organic fraction of municipal solid wastes (MSW) recycles the waste as a safe and nutrient enriched soil amendment, reduces emissions of greenhouse gases and generates less leachate. The objective of this project was to investigate the composting effectiveness of three bulking agents, namely chopped wheat (*Triticum*) straw, chopped mature hay consisting of 80 % timothy (*miliun*) and 20 % clover (*triphullum*) and pine (*pinus*) wood shaving. These bulking agents were each mixed in duplicates at three different ratios with FW and composted for 10 days using prototype in-vessel composters to observe their temperature and pH trends. Then, each mixture was matured in vertical barrels for 56 days to measure their mass loss and final nutrient content and to visually evaluate their level of decomposition. Chopped wheat straw (CWS) and chopped hay (CH) were the only two formulas which reached thermophilic temperatures during the 10 days of active composting when mixed with FW at a wet mass ratio of 8.9 and 8.6:1(FW:CWS and FW:CH), respectively. After 56 days of maturation, these two formulas were well decomposed with no or very few recognizable substrate particles, and offered a final TN exceeding the original. Wood shavings (WS) produced the least decomposed compost at maturation, with wood particles still visible in the final product, and with TN lower than the initial. Nevertheless, all BA produced compost with an organic matter, TN, TP and TK content suitable for use as soil amendment.

Suggested Reviewers:

Effectiveness of three bulking agents for food waste composting

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Abstract

Rather than landfilling, composting the organic fraction of municipal solid wastes recycles the waste as a safe and nutrient enriched soil amendment, reduces emissions of greenhouse gases and generates less leachate. The objective of this project was to investigate the composting effectiveness of three bulking agents, namely chopped wheat (*Triticum*) straw, chopped mature hay consisting of 80% timothy (*miliun*) and 20% clover (*triphullum*) and pine (*pinus*) wood shavings. These bulking agents were each mixed in duplicates at three different ratios with food waste (FW) and composted for 10 days using prototype in-vessel composters to observe their temperature and pH trends. Then, each mixture was matured in vertical barrels for 56 days to measure their mass loss and final nutrient content and to visually evaluate their level of decomposition. Chopped wheat straw (CWS) and chopped hay (CH) were the only two formulas that reached thermophilic temperatures during the 10 days of active composting when mixed with FW at a wet mass ratio of 8.9 and 8.6:1 (FW:CWS and FW:CH), respectively. After 56 days of maturation, these two formulas were well decomposed with no or very few recognizable substrate particles, and offered a final TN exceeding the original. Wood shavings (WS) produced the least decomposed compost at maturation, with wood particles still visible in the final product, and with a TN lower than the initial. Nevertheless, all bulking agents produced compost with an organic matter, TN, TP and TK content suitable for use as soil amendment.

Key words: Food waste, bulking agents, composting formula, temperature, C and N losses.

1. Introduction

For urban centres and rather than landfilling, in-vessel composting is a popular method of recycling the food waste (FW) portion of municipal solid waste (USEPA, 2000). Composting is a biological process which reduces the volume and mass of solid organic wastes, while producing a safe, stabilized and nutrient enriched soil amendment (Pace et al., 1995; Haug, 1980; Mato et al., 1994). When landfilled along with municipal solid waste (MSW), the organic fraction is mostly responsible for the emission of greenhouse gases requiring collection and the generation of leachate requiring treatment (USEPA, 2000).

The formula required to successfully compost FW using the in-vessel technology relies heavily on the type, particle size and quantity of bulking agent (BA) used. Once mixed with the FW, the BA should correct the formula's moisture content to fall within a range of 60% to 80% (Haug, 1993; Pace et al., 1995; Morin et al., 2004). The BA also absorbs part of the leachate produced during the decomposition process, to keep the mixture moist and sustain an active microbial activity. Most bulking agents will act as a buffer against the organic acids produced during the early stages of composting, and, thus, will help maintain the mixture's pH within a range of 6 to 8 (Haug, 1993). Biodegradable C is added with the BA for the microbial immobilization of N and the generation of metabolic heat to reach stabilizing thermophilic temperatures (Diaz et al., 1993; Haug, 1993). Finally, the BA gives structure and porosity to the mixture for proper aeration (Barrington et al., 2000a). Although necessary, the BA needs to be properly selected and used at optimum quantities to minimize its purchasing and transportation costs.

Besides a few studies using sugar cane bagass and rice hulls, woody residues have received the most research attention in terms of composting BA. Being of low biodegradability, wood chips were found to require a minimum free air space of 26% as opposed to the generally recommended free air space of 30% (Eftoda and McCartney, 2004; Haug, 1993). For the composting of the organic fraction screened from the MSW stream, Eftoda and McCartney (2004) found that a volumetric ratio of biosolids to wood chips of 1:2.5 provided the best aeration level for the least BA. Furthermore, wood chips with a small particle size of 5.2 mm resulted in a lower moisture loss as compared to a larger particle size of 40 mm, because of greater resistance to ventilation (Raichura and McCartney, 2006). For the composting of wastewater sludge to maximize the death kinetics of *Salmonella*, Gea et al. (2007) reported that optimal results were obtained with an artificial BA with a particle size of 5 mm, mixed at a volumetric ratio of 1:1. For the composting of raw vegetable waste, McGuckin et al. (1998) demonstrated that uniform air distribution is achieved when the quantity of BA mixed into the formula results in a 50% loss of air viscous energy. Albuquerque et al. (2006) indicated that grape stalks were superior to olive leaves as bulking agent, to enhance the temperature regime developed during the active composting phase.

Considering the focus on woody residues as bulking agent, the main objective of this project was to test other fibrous materials for their composting efficiency. For the composting of FW using an in-vessel system, the project therefore investigated three bulking agents locally available in the Montreal region of Canada, namely chopped wheat (*Triticum*) straw, chopped mature hay consisting of 80% timothy (*miliun*) and 20% clover (*triphullum*) and pine (*pinus*) wood shavings. All bulking agents were tested at

three different mixing ratios, resulting in three different initial moisture contents. The performance of each compost formula was evaluated from its ability to reach thermophilic temperatures and to maintain a pH between 6 and 8 during the active composting stage, to lose the most dry and wet mass during the maturation phase, to decompose to the extent that no substrate particles are visible and, once matured, to offer a final moisture content under 50% with an acceptable level of nutrients (organic matter, TN, TP and TK).

2. Material and methods

2.1. Experimental set-up and substrates

Similar to the horizontal in-vessel system, six urban prototype composters were used to test the compost formulas. These composters were built of double wall polyethylene tubing measuring 1.0 m in length and 0.3 m in inside diameter (Fig. 1). The tubing's corrugated exterior wall glued to a smooth inner wall produced an insulation value of $1 \text{ m}^2 \text{ }^\circ\text{C/W}$. Measuring 25 mm in inside diameter and perforated at every 150 mm, a pipe was inserted horizontally at the bottom of each composter to provide an inlet for cold air expected to flow by convection into the composting mixture and, once warmed, to exit through a 25-mm diameter opening at the top end of the composter (Fig. 1). Each composter was filled to 2/3 capacity with the mixture of FW and BA.

The FW was obtained from the composting centre of the Jeanne Mance Park, located in the Plateau area of the city of Montreal, Canada. Delivered within 2 days of being produced by the local residents, this FW was made up of raw and cooked vegetable and fruit residues and was further checked for foreign material upon reception.

The bulking agents were obtained from the experimental cattle complex of the Macdonald Campus of McGill University, Montreal, Canada. The straw (*Triticum*) and mature hay consisting of 80% timothy (*miliun*) and 20% clover (*triphullum*) were produced on the farm, while the pine (*pinus*) wood shavings were purchased from a local supplier. Before preparing all formulas, the straw and hay were chopped to a length varying between 5 and 25 mm. The WS already offered a small particle size in the range of 5 to 10 mm in length and width, by 1 to 2 mm in thickness. All bulking agents and the food waste were characterized (Table 1).

2.2. Compost formulas

For each BA, mixtures were formulated to obtain a moisture content ranging from 20% to 40% (Tables 2, 3 and 4). Each compost mixture was prepared by individually weighing the FW and BA, manually mixing the materials in a tray and then loading the mixture into duplicate composters. Ammonium nitrate (NH_4NO_3) was added as required by the formulas to balance the C/N ratio between 20 and 25. For chopped wheat straw (CWS), the mixtures offered a dry matter content of 40%, 35%, 30%, 25% and 20%. For chopped hay (CH) and wood shaving (WS) as BA, the mixtures offered a dry matter content of 40%, 30% and 20%. During the 10 days of active composting, each in-vessel prototype was rolled daily to ensure the restructuring of the compost material and to maintain a uniform decomposition as observed when sampling for pH every 2 days.

2.3. Methodology

During each one of the four testing sessions, a BA was randomly selected and three of its formulas were tested in duplicate, once randomly assigned to one of the six in-vessel prototype composters. Once filled, each mixture was monitored for temperature and pH, during a 10-day active composting period, because temperature and pH are excellent composting process indicators (Diaz et al., 1993). For each formula tested, the temperature was measured daily at the center of the compost pile, using a long-stem thermometer (PTC Instruments, Los Angeles, California, USA, model 8500D-II). On alternate days, five samples each weighing 5 g were randomly collected from each composter for pH determination. The leachate produced during the process was not measured and collected for analysis. After testing a BA, the composters were emptied, cleaned and filled once more with the mixtures of another BA.

Once actively composted, the mixtures were emptied into individual cylindrical plastic bins, measuring 360 mm in diameter and 300 mm in depth. These rested on wooden blocks for drainage and natural aeration (Fig. 2). All formulas were matured in these cylinders for 56 days, which corresponded to the recommended 2 months of maturation (Haug, 1993). After maturation, each mixture was weighed, visually examined for decomposition and substrate breakdown, and sampled to determine moisture (MC), organic matter (OM), total Kjeldahl nitrogen (TKN), total phosphorus (TP) and total potassium (TK). These parameters assessed the suitability of each compost mixture for use as agricultural soil amendment (Mato et al., 1994).

2.3 Analytical procedure

Using standard laboratory methods (APHA, 1995), the FW, BA and matured composts were characterized for dry matter (DM), carbon (C), pH, TKN, TP, TK and C/N ratio. Dry matter was determined by drying at 103°C for 24 h (Scientific John by Sheldon Manufacturing Inc., Cornelius, Oregon, USA) and expressed as:

$$DM (\%) = (\text{oven dry sample weight} / \text{wet sample weight}) * 100 \quad (1)$$

The volatile fraction of the dried samples was determined by burning at 550°C in a muffle furnace (Blue M Electric Company, Blue Island, USA) for 4 h. Carbon content was determined by dividing the volatile fraction by 1.83 (Barrington et al., 2002a):

$$C (\%) = (100 - \% \text{ ash}) / 1.83 \quad (2)$$

The TKN, TP and TK were determined by digesting the samples with sulfuric acid and 50% hydrogen peroxide at 500°C for 15 min. The TKN of the digested samples was quantified by measuring its NH₃-N content at a pH of 13, using a NH₃ sensitive electrode (Orion, Boston, Massachusetts, USA, model BCN). Because of the low nitrate and nitrate levels of all materials, TN was equated to TKN. The TP and TK of the digested samples were quantified colorimetrically, at a pH of 7, using a spectrophotometer (Hach, Model DR 5000, Loveland, Colorado, USA).

The pH was determined using a pH/Ion meter (Orion, Boston, Massachusetts, USA, model 450) and a pH probe. All samples were soaked for 24 h without shaking at 5°C, in just enough distilled water to produce a solution in which to place the probe, which corresponded to 20 and 50 ml for 10 g of FW and BA, respectively.

The free air space (FAS) was computed from the wet bulk density and wet particle density of the BA and FW materials. The wet particle density was determined by placing 5 g of material in a graduated cylinder and submerging with kerosene. After initially verifying the density of kerosene (0.78 kg/L) and determining the mass of kerosene added, the particle density was calculated (Barrington et al., 2002b). This wet particle density was then used to compute the FAS of the compost components:

$$FAS (\%) = 100 \times (1 - (BD / PD)) \quad (3)$$

where BD is bulk density in (kg/L) and PD is the wet particle density determined using kerosene (kg/L).

2.4 Statistical procedure

Six composters were used to randomly test one BA and three duplicate formulas at any one time. The temperature and pH regime measured for each duplicate FW and BA mixture were averaged and the standard deviation of their value was calculated using Excel (Microsoft, 2003). ANOVA was used to compare the effect of treatment (BA/FW ratio) on temperature and pH, for each BA, where time was designated as a block. The significant treatments and blocks were identified using Duncan's Multiple Range test (Steel and Torrie, 1986).

3. Results and discussion

3.1. Effect of bulking agent to food waste ratio

Of the compost mixtures using CWS, Fig. 3a and b illustrate the measured temperature fluctuations over time as compared to that of ambient air. The compost

197 mixtures with a DM of 25% and 20% (FW/BA ratios of 5:1 and 8.9:1) reached
198 significantly higher temperatures ($P < 0.05$) as compared to those with a DM content of
199 40%, 35% and 30% (FW/BA ratios of 2:1, 2.5:1 and 3.4:1), but only from days 3 to 5.
200 Compared to the low DM mixtures of 20% and 25%, which reached the thermophilic
201 range of 50°C within 3 days of active composting, two other mixtures with a FW/BA
202 ratio of 2.5:1 and 3.4:1 (30% and 35% DM) performed as well from days 0 to 2
203 inclusively. After 2 days, these higher DM mixtures likely lost moisture below that
204 required to sustain a high microbial activity. Wetting these formulas would likely have
205 helped reach thermophilic temperatures. The 40% DM formula resulted in the lowest
206 temperature regime, never exceeding 40°C.

207 As illustrated in Fig. 4 for CH, only the 20% DM mixture (FW/BA ratio of 8.6:1)
208 demonstrated a statistically higher temperature regime compared to the other mixtures
209 ($P < 0.005$), from days 1 to 6 inclusively. As for the CWS mixture with a FW/BA ratio of
210 8.9:1, the CH mixture with a FW/BA ratio of 8.6:1 reached the thermophilic range of
211 50°C on 3 days. For the other CH mixtures with a FW/BA ratio of 3.3:1 and 1.8:1 (30%
212 and 40% DM), compost temperatures remained below 38°C, as compared to CWS
213 mixtures with a FW/BA ratio of 5:1 and 3.4:1 (25% and 30%) which reached 45°C after
214 1 day. Therefore, and as compared to CWS, CH did not sustain as active a microbial
215 activity for the 30% DM mixture.

216 For the WS illustrated in Fig. 5, only the FW:WS ratio of 7.8:1 (20% DM)
217 produced a significantly higher temperature regime ($P < 0.05$) compared to the other
218 formulas, but no mixture reached the thermophilic range. While the temperature of the
219 FW:WS ratio of 7.8:1 reached 37°C on day 4, that of the other mixtures remained under

35°C against an ambient temperature of 12 to 20°C. The WS formulas did not perform as well as those with CWS and CH. Among all WS formulas, that with 20% DM was the most active but lacked aeration with a low 21% FA as compared to the recommended minimum of 26% (Eftoda and McCartney, 2004).

Besides moisture content, the observed temperature regimes were affected by available C and O₂. With anaerobic digestion, the biodegradable C for different organic wastes is well established: 0.80 to 0.95 for cereal, vegetable and fruit wastes; 0.50 to 0.70 for wheat straw; 0.50 for mature grass hay, and; 0.20 to 0.30 for wood residues (Loehr, 1984). Accordingly, CWS offered the most biodegradable carbon and therefore supported the strongest microbial activity. All CWS formulas exhibited high FAS exceeding 30%, and therefore had sufficient structure for aeration (Table 2). Compared to the CWS mixtures with the same DM, CH offered a weaker biological activity, except for the 20% DM with a high FW:BA ratio, where the FW provided the available C. Again, all CH formulas had exhibited FAS exceeding 30%, and accordingly, the proper structure for aeration (Table 3). The WS mixtures demonstrated the lowest microbial activity, in parallel with the low C biodegradability of the BA. The FW:BA ratio of 7.8:1 offered the most microbial activity, again because of its high FW content increasing the C biodegradability, but lacked available O₂ because of its low FAS of 21% (Table 4). Based on previous work (Eftoda and McCartney, 2004; Tognetti et al., 2006) and the present results, wood residues such as WS should be used in combination with other BA, where the low C biodegradability of wood residues help maintain a porous structure while the other BA provides additional C besides the waste being composted.

3.2. The effect of pH

The initial pH of all CWS mixtures was in the range of 6 to 6.5 (Fig. 6a), as a result of the organic acids contained in the FW (Table 1). The pH of these mixtures had all reached a value near 8.0 by day 7, as the microbial activity degraded the organic acids (Diaz et al., 1993) and as the nitrate added by the N amendment was denitrified and added OH^- (Loehr, 1984). Except for the 40% DM mixture which had already reached alkaline conditions on day 2, there were no significant differences in pH values among the mixtures ($P < 0.05$). The 40% DM mixture (FW/BA ratio of 2:1) reached alkaline conditions earlier than all other CWS mixtures because of its lower FW and therefore faster depletion of organic acids, and; because of its higher amendment in nitrogen, which led to more denitrification leading to alkaline conditions.

Compared to CWS, CH formulas exhibited a slightly lower pH because of its slightly acidic nature (Table 1). During the trial, the pH of all mixtures was not significantly different ($P < 0.05$), starting near 6.0 and slowly climbing on day 7 to a value near 7.0 (Fig. 6b). Compared to CWS, the CH mixtures were also amended with a smaller mass of NH_4NO_3 , leading to less denitrification.

With WS, the initial pH of all mixtures was low (near 5.5) because of the acidic nature of the BA (Table 1). Only the 20% DM mixture (FW/WS ratio of 7.8:1) achieved a significantly higher pH (Fig. 6c) of 7.0, after 7 days of composting ($P < 0.05$), because of a more active microbial degradation of the FW and its organic acids, and the denitrification of the nitrate component of NH_4NO_3 . This change in pH occurred gradually from days 3 to 7. Denitrification activity was likely initiated on day 3 along

with an increase in microbial activity reflected by higher temperatures. When analyzing the compost after 56 days of maturation, the WS mixtures had lost the most nitrogen.

3.3. Extent of decomposition

For CWS after 56 days of maturation, the 20% DM formula (FW/BA ratio of 8.9:1) demonstrated a dark brown colour and no recognizable substrate particles. The 25% DM mixture (FW/BA ratio of 5:1) was also highly decomposed and of a dark brown colour; however, some of the wheat straw was not fully decomposed.

Although dark brown in colour, none of the CH mixtures were fully decomposed after 56 days of maturation because a limited amount of hay particles were still visible. The hay used in this trial was mature and coarse when harvested and therefore less biodegradable than straw and hay cut early. Nevertheless, the CH mixture with a 20% DM (FW/BA ratios of 8.8:1) offered the least recognizable BA particles.

After 56 days of maturation, the WS mixtures (FW/BA ratios of 1.5:1, 2.9:1 and 7.8:1) offered the least BA decomposition, compared to the CWS and CH mixtures. Only the 20% DM mixture had developed a brown colour, because of the greater mass of decomposed FW, compared to the other WS mixtures.

After 56 days of maturation, the degree of visual decomposition varied in direct relation with the temperature reached during the active composting phase and the C biodegradability of the BA. The CWS offered the most biodegradable C, leading to a high degree of BA decomposition; the CH suffered less decomposition compared to CWS because it consisted of mature coarse grasses with some clover, which offered a lower

amount of degradable C. The WS with the lowest C biodegradability suffered the least decomposition after 56 days of maturation.

3.4. Mass reduction of compost mixtures after maturation

After 56 days of maturation with CWS, the wet mass reduction for the 40%, 30%, 25%, and 20% DM mixtures was 62%, 70%, 77% and 86%, respectively (Table 5). A major portion of this mass reduction resulted from the loss of water through evaporation and leaching (Table 6), because the 20% and 25% DM formula (FW/BA ratio of 5:1 and 8.9:1, respectively) lost 0.73 and 0.67 kg of water per kg of initial wet compost mass, respectively. Their dry mass was reduced by 39% and 68%, resulting in 55 and 42 g of C lost/kg of initial wet compost or 210 and 220 g/kg of initial dry mass, for the 20% and 25% DM formulas, respectively. This dry mass reduction corresponds to the temperatures of 55 and 52°C reached during the active composting process.

The mass reduction for the CH mixtures after 56 days of maturation was found to be proportional to the initial MC, because, again, most of the mass reduction was associated with the evaporation and leaching of moisture (Table 5). The 20% CH mixture (FW/BA ratio of 8.6:1) lost 84% of its wet mass, including 0.67 kg of water per kg of initial wet compost (Table 6). The CH mixture with 20% DM also lost 285 g of C/kg of initial dry matter, an amount superior to that observed with CWS for the same initial DM.

The wet mass reduction obtained with the WS mixtures was relatively low, at 26% and 40%, for the 40% and 30% DM (FW/BA ratios of 1.5:1 and 2.9:1), respectively, because of the low level of microbial activity obtained during the active composting phase, as indicated by the low temperature regimes. Only the WS mixture with 20% DM

(FW/BA ratio of 7.8:1) lost 71% and 50% of its wet and dry mass, representing 0.61 kg of water and 10 g of C/kg of initial wet compost mixture. For the formulas with an initial 20% DM, the final moisture content of 66% obtained with the WS mixture was still higher than that for the corresponding CWS and CH mixtures, because of the lower temperature regime developed during the initial composting stage.

The amount of C lost per initial amount of dry matter was proportional to the temperature regime obtained against the ambient air temperature. An average temperature differential between the compost and the ambient air of 26°C for 5 days (130°C-d), 31 and 23°C for 3 and 4 days (93 and 132°C-d), and 13°C for 5 days (65°C-d) was obtained with the CH formula at 20% DM, the CWS formulas at 20% and 25% DM, and the WS formula with 20% DM. In exchange, the C losses were on the order of 57, 42, 55 and 10 g/kg of initial wet mass.

In terms of N losses, the CWS with an initial 25% DM experienced the least losses at 1.0 g/kg of initial wet compost mass (4 g/kg of initial dry mass), followed by the CH and CWS with an initial 20% DM losing 2.7 and 3.2 g of N/kg of initial wet compost mass (13.5 and 16.0 g/kg of initial dry mass). The WS with an initial 20% DM lost the most N, at 4.0 g/kg of initial wet compost mass (Table 6). For CWS, the 25% DM formula lost less N compared to that with 20% DM, likely because of less leaching.

3.5. Agricultural value of the finished composts

The CWS (20% and 25% DM), CH (20% DM) and WS (20% DM) matured composts offered an OM content exceeding 40% and TKN, TP and TK levels exceeding 2.5%, 0.25% and 3.0%, respectively, on a dry matter basis (Table 6). These parameters

are within the range required for agricultural use as soil amendment, according to Tognetti et al. (2006).

The mature CWS and CH formulas offered a TN which exceeded their original content by 85% and 25%, respectively, whereas the mature WS formula offered a TN which was 60% lower than its original. The high nitrogen losses obtained with the WS mixture resulted from the relatively large mass of ammonium nitrate required initially to balance the C:N ratio and the lower C biodegradability of the BA, which failed to provide substrate for microbial N immobilization. Similar high losses in N were observed by Tognetti et al. (2006) while composting with wood shavings the organic fraction screened from the municipal solid waste stream.

Compared to that of CWS and WS, the matured CH formula offered a higher TP content simply because of the generally higher phosphorous content of BA consisting of grasses and clover. All BA formulas offered relatively high TK contents, exceeding 2.9% (wet mass) because of the generally rich potassium content of FW.

Because all bulking agents with an initial 20% DM exhibited over 50% and 70% dry and wet mass losses, respectively, once matured, composting can be said to reduce the storage space required and lower the transportation cost, compared to the raw FW mass. Finally, with a final DM under 50%, these composts are less attractive to insects (Connell, 1992).

4. Conclusion

The objective of the project was to test three bulking agents (BA), at three moisture levels, for the composting of food waste (FW) consisting of raw and cooked

vegetables and fruits residues. The best compost formula was expected to reach thermophilic temperatures during its active composting stage, to lose the most dry and wet mass during its maturation phase, to decompose to the extent that no substrate particles would be recognizable, to offer a final moisture content under 50% and to hold an acceptable level of nutrients (TN, TP and TK) once matured.

With a FW ratio resulting in a 20% dry matter content (DM), the chopped wheat straw (CWS) and chopped hay (CH) formulas met the above criteria. On a wet mass basis, these formulas required the mixing of 8.9 and 8.6 kg of FW for every 1.0 kg of BA. These two formulas reached thermophilic temperatures during the active composting stage, despite the high surface-to-volume ratio of the prototype in-vessel composters used; produced mature compost with a final DM of 46% to 65%, where no or very little substrate particles could be recognized; offered a final TKN, TP and TK content exceeding, respectively, 2.5%, 0.20% and 3.0% on a dry basis; and resulted in more than 50% losses in wet and dry mass. The 20% DM formula using pine wood shavings (WS) as bulking agent did not reach thermophilic temperatures during the active composting stage and wood particles were still quite visible after 56 days of maturation, although 50% and 71% of the dry and wet masses, respectively, were lost. For the 20% DM formulas, WS lost a substantial amount of nitrogen through volatilization and leaching, which resulted in a final TKN content lower than the initial, whereas for CWS and CH, the final N content was higher than the initial. Further research is needed to test WS in combination with CWS and CH.

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Nomenclature

BA – bulking agent;

BD – wet bulk density;

C - carbon

CH – chopped hay;

C/N – carbon to nitrogen ratio;

CWS – chopped wheat straw;

DM – dry matter;

DW – dry weight basis;

FAS – free air space offered by compost mixture or bulking agent;

FW – food waste;

MC – moisture content, or dry mass divided by wet mass;

MSW – municipal solid waste;

N – nitrogen;

OM – organic matter;

TKN – total Kjeldahl nitrogen;

TK – total potassium;

TP – total phosphorous;

WS - wood shaving.

Fig. 1. Experimental in-vessel composter.

Fig. 2. Vertical plastic bin used to mature the composted mixtures.

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(a)

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(b)

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Fig. 3. Temperature variation with time for food waste (FW) and chopped wheat straw (CWS) formulas where the vertical bars are standard deviation: (a) 8.9:1, 2:1 (b) 5:1, 3.4:1, 2.5:1

1

Fig. 4. Temperature variation with time for the food waste (FW) and chopped hay (CH) formulas where the vertical bars are standard deviation.

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Fig. 5. Temperature variation with time for the food waste (FW) and wood shavings (WS) formulas where the vertical bars are standard deviation.

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Fig. 6. Variation in pH with time for food waste (FW) and bulking agent formulas where the bar at the top of each column is the standard deviation: (a) FW and chopped wheat straw (CWS) (b) FW and chopped hay (CH) (c) FW and wood shaving (WS).

Table 1 Characteristics of experimental food waste (FW) and bulking agents (BA)

Parameters	Food waste (FW)	Chopped wheat straw (CWS)	Chopped hay (CH)	Wood shavings (WS)
pH	4.1 (0.2)	7.0 (0.6)	6.6 (0.5)	5.6 (0.3)
Dry matter, %	12.2 (1.3)	89 (1.3)	91 (1.4)	80 (0.2)
Carbon, %	47.4 (3.1)	50.4 (1.0)	51.7 (0.6)	54.5 (0.02)
TKN, %	2.0 (0.3)	0.5 (0.08)	0.9 (0.12)	0.08 (0.01)
C/N ratio	24 (3.0)	103 (16)	59 (9)	676 (11)
Wet bulk density, kg/m ³	410 (92)			
Particle size, mm	10-100	5 - 25	5 - 25	5 - 10
Loose (no compression)		16	43	84
Medium manually compressed (3kPa)		38	75	116
Manually compressed (6kPa)		68	109	151
Machine compressed (as packaged by supplier)		127	-	211

Note: Numbers in parenthesis is the standard deviation.

Table 2 Trial formulas of food waste (FW) and chopped wheat straw (CWS)

Formula Number	FW:CWS WW	FW:CWS DW	NH ₄ NO ₃ % WW	NH ₄ NO ₃ % DW	C/N before amending	C/N after amending	DM %	BD kg/m ³	FAS %
1	2.0:1 (1:5)	-	1.80	-	-	20.2	40	175	73
2	2.5:1 (1:4)	1:3.1	1.43	4.1	57	20.9	35	202	70
3	3.4:1 (1:3)	1:2.4	1.15	3.8	53	20.9	30	253	64
4	5.0:1 (1:2)	1:1.5	0.87	3.5	45	20.9	25	378	49
5	8.9:1 (1:1.3)	1.2:1	0.59	3.0	39	20.9	20	560	30

Note: WW – wet weight basis; DM – dry weight basis; DW – dry weight basis; BD – bulk density under a pressure of 6 kPa; FAS – free air space under a pressure of 6 kPa; numbers in parenthesis is the volumetric ratio.

Table 3 Trial formulas of food waste (FW) and chopped hay (CH)

Formula	FW:CH	FW:CH	NH ₄ NO ₃	NH ₄ NO ₃	C/N	C/N	DM	BD	FAS
Number	WW	DW	% WW	% DW	before amendment	after amendment	%	kg/m ³	%
1	1.8:1 (1:3)	1:4.31	0.70	1.7	41	21	40	283	67
2	3.3:1 (1:1.6)	1:2.23	0.49	1.6	35	21	30	344	60
3	8.6:1 (1.5:1)	1.12:1	0.29	1.4	27	21	20	570	39

Note: WW – wet weight basis; DM – dry weight basis; DW – dry weight basis; BD – bulk density under a pressure of 6 kPa; FAS – free air space under a pressure of 6 kPa; numbers in parenthesis is the volumetric ratio.

Table 4 Trial formulas of food waste (FW) and wood shaving (WS)

Formula	FW:WS	FW:WS	NH ₄ NO ₃	NH ₄ NO ₃	C/N before	C/N after	DM	BD	FAS
Number	WW	DW	% WW	% DW	amendment	amendment	%	kg/m ³	%
1	1.5:1 (1:2.3)	1:4.48	2.3	5.7	123	21.02	40	520	52
2	2.9:1 (1:1.2)	1:2.32	1.5	5.0	79	21.36	30	599	40
3	7.8:1 (2:1)	1.14:1	0.74	3.7	46	21.36	20	750	21

Note: WW – wet weight basis; DM – dry weight basis; DW – dry weight basis; BD – bulk density under a pressure of 6 kPa; FAS – free air space under a pressure of 6 kPa; numbers in parenthesis is the volumetric ratio.

Table 5 Mass reduction of test formulas for various bulking agents after 56 days of maturation

FW:CWS	% MR		MC	FW:CH	% MR		MC	FW:WS	% MR		MC
	DW	WW			DW	WW			DW	WW	
2:1	-	62	-	1.8:1	-	57	-	1.5:1	-	26	-
3.4:1	-	70	-	3.3:1	-	69	-	2.9:1	-	40	-
5:1	39	77	35	8.6:1	52	84	40	7.8:1	50	71	66
8.9:1	68	86	54								

Note: MR – mass reduction; DW - dry weight basis; WW - wet weight basis; MC - moisture content.

Table 6 Nutrient content and C, N and water losses for the mature compost

Parameter	Suggested ***	Food waste to bulking agent mixture			
		FW:CWS	FW:CH	FW:WS	
FW/BA		5:1	8.9:1	8.6:1	7.8:1
MC, %	<40	35	54	40	66
OM, % DW	>25	39	42	40	51
TKN, % DW	>0.6	3.72 (2)	3.04 (2.4)	2.6 (1.97)	0.95 (2.4)
TP, % DW	>0.22	0.29	0.24	0.41	0.25
TK, % DW	>0.25	3.09	3.16	3.07	2.9
BD, kg/m ³	-	630	630	630	460
C lost, g/kg*		55	42	57	10
N lost, g/kg*		1.0	3.2	2.7	4.0
H ₂ O lost, kg/kg*		0.73	0.67	0.74	0.61
H ₂ O lost, kg/kg**		9.5	6.7	7.1	61

Note: FW/BA – food waste to bulking agent ratio on a wet mass basis; MC – moisture content; OM – moisture content; BD – bulk density at a pressure of 6 kPa; DW - dry weight; the number in parenthesis is the % TKN(DW) of mixture before starting the composting process; * based on 1.0 kg of initial mixture on a wet mass basis; ** moisture lost per kg of dry matter lost; ***according to Tognetti et al. (2006).

WM-7- 244 response

Response to reviewers' comments

Reviewer 1

The introduction was shortened and modified with more recent references more appropriate to the topic.

CWS was modified in the nomenclature

In table 6, the MC is 66% and the OM is 51 % of the dry mass; these do not have to add up to 100%.

Reviewer 2

All grammar corrections were carried out and the reference section was updated as well as corrected.

The word “recipe” was changed for “formula”.

The Latin words were added for the BA types.

The degree of decomposition was evaluated visually. This was added to the text of the methodology and results.

The best compost mixture was defined under the objectives (lines 87-91).

Line 48 Jeanne Mance was irrelevant and removed.

Other relevant studies: the literature review was modified to this effect.

The type of food waste was described on line 106-107.

A statistical analysis section was added.

The $P < 0.5$ was corrected to $P < 0.05$ or $P < 0.005$, where concerned.

The significant differences in temperature regime were identified in the first section of the results.

The amount of dry and wet masses lost during the composting process is indicated in Tables 5 and 6. Table 6 has been modified to show the amount of water, C and N lost.

Reference is clearly indicated to losses through leaching and volatilization of both moisture and nitrogen; this is indicated at several places such as lines 296 and 303.

All figures were corrected as suggested.

Reviewer 3

Grammar corrections were introduced.

Figure titles were corrected as suggested.

Figure 6 was not deleted, as we feel that it is important in illustrating differences and variation in pHs. Also this paper does not have an extensive number of figures.

Reviewer 4

Section on page 4, lines 69-71 was removed. The entire introduction was modified and better adapted to the topic.

The filling of the composters to 2/3 capacity has no impact on the % of mass lost.

The daily rolling of the prototypes was to restructure the compost and keep it homogeneous; text corrected; line 127-129.

Dashed lines are introduced in the figures to differentiate between treatments; the practice of using solid lines for models is not standard.