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What scientific issues in life cycle assessment applied to waste and biomass valorization? Editorial

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ORIGINAL PAPER

Biodegradability of Municipal Organic Waste: A Respirometric Test

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Abstract Home composting of the organic fraction of the municipal solid waste mainstream can help reduce the economic and environmental burden currently faced by urban centres. The physico-chemical properties of the organic fraction components, mainly food waste (FW) and yard trimmings (YT), govern the process effectiveness, namely its rate and extent. The objective of the study was to identify the most effective home composting formula using respirometric tests measuring oxygen uptake. Pure, binary and tertiary formulas of FW, YT and wood chips (WC) were aerated for 32 days in cells maintained at 40 °C. Results indicated that the formula composition had a significant impact on the rate and cumulative O_2 uptake ($p < 0.01$). The binary formula of FW:YT with a wet volume fraction of 0.5:0.5 produced the highest peak O_2 uptake rate (OUR) and cumulative oxygen uptake (COU) of 145 mol/h/kg dm and 28.4 mol/kg dm, respectively, followed by the tertiary formula of FW:YT:WC with a fraction of 0.33:0.33:0.33, at 115.6 mol/h/kg dm and 15.3 mol/kg dm. Considering peak OUR and COU, the binary formula of FW and YT is thus most effective in supporting an active microbial activity for a fast composting process and the generation of high temperatures. Accordingly, adding WC as bulking agent is not necessary.

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Abbreviation

C/N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DM	Dry matter
FAS	Free air space
FW	Food waste
H_2SO_4	Sulphuric acid
$K_2Cr_2O_7$	Potassium dichromate
M1	Pure formula of food waste
M2	Pure formula of yard trimmings
M3	Pure formula of wood chips
M4	Binary formula of food waste and yard trimmings
M5	Binary formula of food waste and wood chips
M6	Binary formula of yard trimmings and wood chips
O_2	Oxygen
OM	Organic matter
TC	Total carbon
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TM	Tertiary formula of food waste, yard trimmings and wood chips
WC	Wood chips
YT	Yard trimmings

Introduction

Because of its biodegradability and its importance within the municipal solid waste mainstream, the organic waste fraction must be properly managed to prevent environmental issues [1–3] Mainly composed of food waste (FW) and yard trimmings (YT), the organic waste fraction of municipal solid waste is subjected to recycling policies in Europe and North America aimed at landfill diversion [4, 5], thus minimizing greenhouse gas emissions and risks of groundwater contamination. The composting of organic waste is one of the options achieving this recycling goal with minimal environmental and economic impact [6, 7]. As bulking agent, wood chips (WC) improve aeration by providing a stable structure and buffering the moisture content. By reducing handling, transportation, labour and infra-structure costs associated with centralized facilities, home composters are recognized as an economical and practical method for organic waste recycling [8]. Nevertheless, optimal home composter formulas have yet to be determined to optimize the effectiveness of the process, namely minimize the size of the system and maximize the stabilizing temperatures and organic waste mass reduction.

For an effective organic waste composting operation, microbial activity must be optimized during the initial phase of the process [9, 10]. In turn, microbial activity is affected by the physico-chemical properties of the organic waste formula, such as moisture content, particle size, free air space, C:N ratio and pH [11, 12]. Microbial activity is reflected through its oxygen uptake rate (OUR) and cumulative oxygen uptake (COU) over time [13, 14]. Respirometry is recognized as a scientifically accepted procedure for the study of microbial activity during the degradation of organic waste [15, 16]. Oxygen uptake rate (OUR) is a meaningful biological indicator because it corresponds to the rate at which microbes utilize oxygen to mineralize carbon and to carryout out their metabolic activities [9, 17]. Recently, respirometric tests were used to measure inhibition effects, kinetics parameters and compost maturity, beside organic waste decomposition rate [18, 19].

Respirometric techniques measure oxygen consumption rather than CO_2 production, since CO_2 production depends on the oxidation degree of carbon and whether the reaction is aerobic or anaerobic, resulting in the production of a O_2:CO_2 molecular ratio other than the theoretical value of 1.0. Furthermore, respirometric tests can be either static or dynamic [20]. Static respirometry is performed using solid or water submerged organic waste without the constant addition of oxygen as opposed to dynamic respirometry [21, 22] where oxygen is constantly applied. To measure the biodegradability of organic waste formulas, dynamic systems are preferred as larger samples can be analyzed, thus better representing industrial processes. Furthermore, gas pocket formation is prevented thus providing a more accurate measurement of O_2 consumption [15, 23].

Respirometric tests were therefore used in this study to identify optimal home composter formulas. Pure, binary and tertiary formulas were prepared using FW, YT and WC, according to recommended practices of using a bulking agent consisting of wood chips. All formulas were prepared based on a wet volume fraction, the standard measurement used by residents to fill their home composter. The formula oxygen uptake rate (OUR) and cumulative oxygen uptake (COU) were used to compare levels of microbial activity and formula decomposition rate and extent.

Materials and Methods

Experimental Materials and Set-up

Collected from 3 restaurants of the city of Rennes, France, the source separated food waste (FW) consisted mainly of fruit and vegetable residues. Obtained from the green space of the Rennes Cemagref Research Centre, France, the yard trimmings (YT) were composed of 90 % grass clippings and 10 % dry tree leaves on a wet mass basis. Wood chips (WC) from crushed wood pallets were screened to obtain particles varying in size from 5 to 20 mm in width and 30–90 mm in length. These experimental materials are described in Table 1.

Test formulas represented pure, binary and tertiary blending of FW, YC and WC. The pure formulas used only one material while the binary and tertiary formulation included two and three materials, respectively. On a wet volume fraction: the pure experimental formulas were M1 (FW only), M2 (YT only) and M3 (WC only); the binary experimental formulas were M4 (FW:YT = 0.5:0.5), M5 (FW:WC = 0.5:0.5) and M6 (YT:WC = 0.5:0.5), and; the tertiary experimental formulas was TM (FW:YT:WC = 0.33:0.33:0.33), tested 3 times (TM1, TM2, TM3). These formulas represented central and extreme points for the modeling by Multivariable Linear Regression, of the impact of individual components on oxygen uptake. Figure 1 illustrates the triangular coordinates of the test formulas. The vertices, sides and centre of the triangle illustrate pure, binary and tertiary formulas of FW, YT and WC.

The respirometric apparatus (Fig. 2) consisted of 6 stainless steel 10 L respirometric cells equipped with a bottom and top air inlet and outlet. The respirometric cells and their content were kept at 40 °C by means of a water bath heated by an automated system (Polystat 71, Huber, Offenburg, Germany). The temperature of the cell content was also manually recorded using a Platinum resistance thermometer (Pt 100 probe, model TTR3, Endress 1 Hauser, Huningue, France). A temperature of 40 °C was found to optimize microbial activity for solid organic wastes [24].

Aerobic conditions were maintained by supplying each cell with a continuous air flow rate of 75 ± 5 L/h, re-circulated to ensure homogenous conditions throughout

Table 1 Characteristics of experimental food waste, yard trimmings and wood chips

Characteristics	Food waste (FW)	Yard trimmings (YT)	Wood chips (WC)
DM (%)	21.3 (0.5)	60.4 (8.0)	93.0 (0.4)
TC (% dm)	42.4 (2.0)	35.3 (2.0)	46.3 (0.8)
COD (g/kg dm)	1,205 (51)	1,002 (106)	1,228 (91)
TKN (g/kg dm)	21.0 (0.7)	19.0 (1.4)	9.7 (0.8)
C:N	20.2	18.6	47.7
pH	5.3 (0.1)	6.8 (0.7)	5.6 (0.2)
OM (% dm)	82.1 (2.3)	69.7 (3.8)	97.8 (0.5)
OM:TC ratio	1.94	1.97	2.11
Organic fractions			
Soluble (% OM)	65.7 (5.6)	34.0 (3.0)	7.40 (1.0)
Hemicellulose (% OM)	19.2 (5.6)	26.6 (7.8)	18.6 (0.9)
Cellulose (% OM)	12.0 (0.6)	24.3 (0.8)	55.8 (1.0)
Lignin (% OM)	3.1 (0.7)	15.2 (7.0)	18.2 (2.6)

DM dry matter, *TC* total carbon, *COD* chemical oxygen demand, *TKN* total Kjeldahl nitrogen, *OM* organic matter, *dm* dry mass

Numbers in parentheses are standard deviation (n = 3)

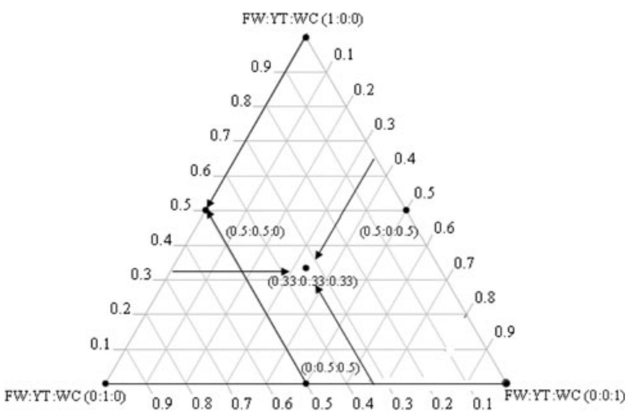

Fig. 1 Triangular coordinates of tested formulas for FW, YT and WC. *FW* food waste, *YT* yard trimmings, *WC* wood chips. *Note*: all components are presented as a fraction of the total wet volume ranging from 0 to 1. The *left axis* gives FW, the *right axis* gives WC and the *bottom axis* gives YT. The *arrows* show how to interpret the value of two of the illustrated points

the material. Each individual cell was aerated using an air pump (model DH-106-1, Koratsu Equipments Inc., Japan) regulated using a volumetric air flow meter (Barnant Gilmont Industrial flow meter, Barrington, Illinois, USA). The outgoing and incoming volumetric air flow rate was verified by manually recording on a daily basis the cumulative volumetric air flow registered by gas flow monitors (model Gallus 2000 1.6, Itron, Reims, France). For each cell in sequence, the incoming and then the outgoing air composition (CO_2 and O_2) were measured every 2 min during 15 min using an ADC gas analyzer (model MGA 3000, ADC, Hertfordshire, England) with an accuracy of ±0.1 % for O_2 and ±1 % of the reading for CO_2. This 6-cell monitoring sequence was repeated throughout the experimental period.

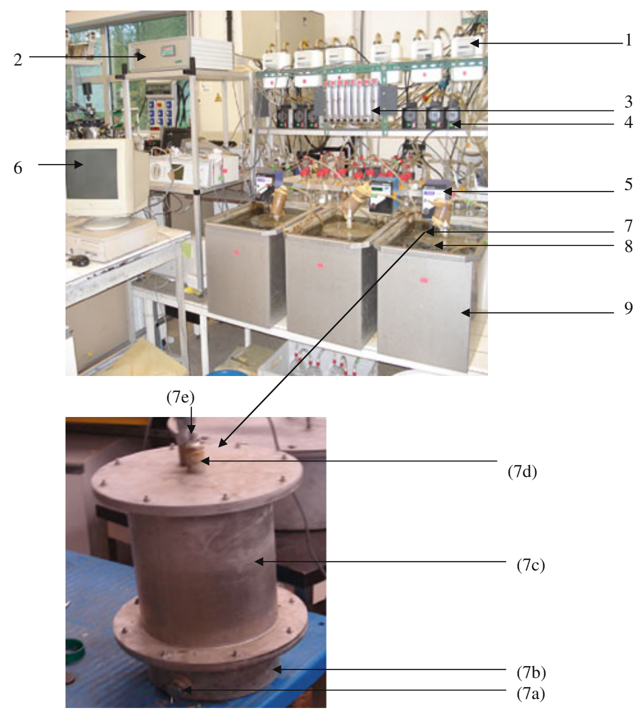

Fig. 2 Experimental setup for respirometric tests. *1* cumulative volumetric air flow counters; *2* air component analyzer; *3* volumetric air flow meters; *4* air circulation pump; *5* water bath heater with thermostat; *6* results display screen; *7* respirometric cell: (*7a*) air inlet port, (*7b*) leachate collector, (*7c*) organic formula chamber, (*7d*) temperature sensor port, (*7e*) air outlet port; *8* water maintained at 40 °C; *9* water tank

Experimental Procedure

The experimental set-up tested 6 formulas at any one time. Overall, 9 formulas were tested: the 3 single pure formulas, the 3 single binary formulas and the single but triplicate tertiary formula. The test reproducibility of the experimental procedure was verified by means of the triplicate tertiary formulas.

During each test, the respirometric cells were individually filled with one formula of known wet and dry mass and without compaction. After filling each cell, the free air space (FAS) of the formula was determined using an air pycnometer [14] which consists in pressurizing air inside an airtight cell while measuring the volume of injected air. At equilibrium pressure, the injected air provides an estimate of free air space in the test formulas.

After characterizing its physical properties once in the cell, each formula was aerated for 32 days at 75 L/h without being mixed. The O_2 and CO_2 concentrations of the incoming and outgoing air flow were monitored to compute the oxygen uptake rate (OUR) over time using the following equation:

$$OUR = Q(O_{2\,in} - O_{2\,out})V^{-1}M^{-1} \quad (1)$$

where OUR is the oxygen uptake rate in mmol O_2/h/kg dm; Q is air flow rate in L of air/h ($O_{2\ in} - O_{2\ out}$) is the difference in O_2 concentration between in the inlet and outlet air streams of the respirometric cell in L of O_2/L of air; V is the volume occupied by 1 mmol of gas/L at 40 °C and 101 kPa of atmospheric pressure, and M is the initial dry mass of the formula in kg. The oxygen uptake was simply compiled from the OUR. All cells were maintained at 40 °C to be able to compare their biodegradability under the same optimal conditions.

At the end of the 32 day respirometric test, each formula was removed from its cell, weighed and sampled for characterization. Accordingly, a mass balance analysis was conducted on the dry matter (DM), water, total carbon (TC), organic matter (OM) and nutrient content of the treated formulas.

Analytical Procedures

The chemical characteristics of the raw materials and of the 32 day formulas were determined on triplicate samples dried in an oven (SR 2000, Thermosi, France) at 80 °C until a constant weight was reached (24 h), and then grinded to less than 0.5 mm (ZM model 1000 grinder, Retsch, Germany).

Dry matter was determined by weight loss after drying in an oven (SR 2000, Thermosi, France) at 80 °C for 24 h and then 103 °C for 1 h. Total carbon (TC) was determined using an Organic Element Analyser (Thermo Scientific FLASH 2000 Series, Courtaboeuf, France) by burning 10 mg samples at 900 °C according to [25]. Total Kjelhahl nitrogen (TKN) was analyzed according to [26] using an automatic distilling system (VAP 50c, Gehardt automatic distilator, Gehardt, Germany) to digest 0.5–1.0 g samples with H_2SO_4 (automated Kjeldatherm TZ block digester, Gerhardt, Germany). After digesting 60 mg samples with H_2SO_4 and $K_2Cr_2O_7$ (Kjeldatherm COD digestion block, CSB 20 M, Gerhardt, Germany), the chemical oxygen demand (COD) was determined by titration (Metrohm, Courtaboeuf, France) according to [27].

According to [28], the organic matter (OM) was determined by burning samples at 550 °C for 3 h (Thermolyne 30400, Furnace, F30420 C-33, Essex, UK). The pH of wet samples was determined by soaking for 24 h without shaking at 5 °C, in just enough distilled water (pH-Electode SenTix41, WTW, Weilhein, Germany). The soluble organic, hemicellulose, cellulose and lignin fractions, were determine using a fibre extractor (VELP Scientific, FIWE 6 Extractor for raw fibre determination, Usmate, Italy) according to [29]. This method of analyzing the different organics fractions establishes the biodegradability of organic compounds [30].

Statistical Procedure

The formulas respected a custom mixture design [31] consisting of the three pure formulas with FW, YT or WC, three binary formulas with a combination of 2 out of the 3 experimental materials, and a tertiary formula with all 3 experimental materials. To evaluate differences between test formulas, the physico-chemical characteristics of the triplicate samples collected were also compared using analysis of variance (ANOVA) at a 95 % confidence level (SAS Institute Inc., Cary, NC, USA, 2008).

Using the statistical software package SAS, peak oxygen uptake rate values were fitted to a Multivariate Linear Regression model and the model coefficients were evaluated for significance at a confidence level of 95 % [31]. This model deciphered the association between peak OUR and formula constituents FW, YT and WC, including their interactions. The regression model was:

$$\begin{aligned} OUR_P = {} & (C_1 \times FW) + (C_2 \times YT) + (C_3 \times WC) \\ & + (C_{12} \times FW \times YT) \\ & + (C_{13} \times FW \times WC) + (C_{23} \times YT \times WC) \\ & + (C_{123} \times FW \times YT \times WC) \end{aligned} \quad (2)$$

where OUR_p is the peak OUR in mmol/h/kg dm; C_1, C_2, C_3, C_{12}, C_{13}, C_{23} and C_{123} are the model coefficients and FW, YT, WC are the wet volumetric fraction of FW, YT and WC, respectively. The coefficient of determination between the measured and model estimated peak OUR was computed for all experimental formulas to test model validity.

The coefficient of variation among peak OUR values for repeated tests was evaluated as [32]:

$$CV = \frac{S}{\overline{\overline{X}}} \times 100 \quad (3)$$

where CV is the coefficient of variation in %, S is the sample standard deviation and $\overline{X}$ is the sample mean.

Results and Discussions

Characteristics of the experimental materials and respired formulas

The experimental materials offered different ($p < 0.05$) physico-chemical characteristics. At 21.3 % dry matter (DM), FW offered a higher moisture content than YT and WC, at respectively 60.4 and 93.0 % DM (Table 1). The YT offered less total carbon (TC), organic matter (OM) and chemical oxygen demand (COD) because of a greater mineral content. The FW and WC offered a slightly acid pH as compared to the neutral pH of YT. The fractional analysis of organics demonstrated a higher soluble fraction for FW at 65.7 % of the total OM, followed by YT at 34.0 % and WC at 7.4 %. Inversely, a higher lignin content was observed for WC at 18.2 % of the total OM, followed by YT at 15.2 % and FW at 3.1 %. Accordingly and as compared to YT and then WC, FW offered the most opportunity for biodegradation, depending on environmental conditions and microbial populations, formula physico-chemical properties and aeration performance. Food waste offered a higher soluble organic matter and lower lignin fraction, suggesting a more extensive biodegradation, as long as its moisture content is corrected with another waste or by means of a bulking agent.

The initial characteristics of the experimental formulas are presented in Table 2. The characteristics of the tested formulas differed significantly ($p < 0.05$). Formulas with FW, alone or in combination with YT offered a DM of 21–25 %, while formulas with WC offered a DM of 36–38 %. Whenever present and because of its high moisture content, FW produced a formula wet bulk density of 0.4–0.5 kg/L, as compared to 0.1–0.2 kg/L when absent. All experimental formulas offered high FAS of at least 61 %, with the inclusion of WC producing higher values reaching 94 %. While FW and YT offered a low C:N ratio of 20.4 and 18.5, respectively, WC offered a high ratio of 48.0. Although known to produce higher N losses, a low C:N ratio is also known to enhance microbial activity and produce earlier temperature peaks [33]. Accordingly, formulas with YT and FW were expected to produce peak OUR earlier than those with WC. All experimental formulas offered a COD value significantly different ($p = 0.01$) in the range of 1,000–1,220 g/kg DM, and an organic matter content (OM) of 70–92 % based on DM with significant differences ($p < 0.05$).

Considering recommended composting values for DM in the range of 20–40 %, FAS above 30 % and C:N ratio under 35, experimental formulas M1 (FW alone), M4 (FW with YT) and M5 (FW with WC) and TM (FW, YT and WC) offered adequate physico-chemical properties [11, 12]. Experimental formulas M2 (YT), M3 (WC) and M6 (YT and WC) were relatively dry, with formulas M3 and M6 offering a C:N ratio above 35.

Table 3 presents the characteristics of the formulas after 32 days of respirometry. These characteristics differed significantly ($p < 0.05$) amongst the test formulas. All formulas with an initial DM under 40 % lost over 36 % of

Table 2 Initial characteristics of experimental formulas using food waste, yard trimmings and wood chips

Characteristics	Mixtures								
	M1	M2	M3	M4	M5	M6	TM1	TM2	TM3
Wet mass (kg)	3.3	0.5	1.2	2.9	3.1	1.0	3.1	2.6	2.5
Dry mass (kg)	0.7	0.3	1.1	0.7	1.2	0.9	1.1	1.0	0.9
DM (%)	21.3 (0.5)	60.4 (8.0)	92.8 (0.4)	25.1 (0.3)	39.7 (0.4)	83.3 (2.4)	36.2 (0.2)	38.1 (0.2)	36.8 (0.3)
Wet bulk density (kg/L)	0.5	0.1	0.2	0.5	0.5	0.1	0.4	0.4	0.4
FAS (%)	61.6	95.2	89.5	66.3	64.4	94.0	79.6	70.2	69.0
TC (% dm)	42.4 (1.9)	35.3 (1.9)	43.0 (1.0)	40.8 (1.3)	44.8 (1.2)	44.0 (0.4)	43.5 (1.1)	43.5 (1.0)	43.2 (1.0)
TKN (g/kg dm)	20.8 (0.7)	19.0 (1.4)	9.0 (0.7)	20.4 (0.4)	14.1 (0.4)	10.9 (1.0)	15.6 (0.3)	15.3 (0.3)	15.7 (0.3)
C:N ratio	20.4	18.5	48.0	20.0	31.7	40.3	27.9	28.5	27.4
COD (g/kg dm)	1,205 (51)	1,002 (106)	1,140 (83)	1,159 (27)	1,219 (55)	1,182 (64)	1,196 (36)	1,194 (37)	1,189 (31)
OM (% dm)	82.1 (2.3)	69.7 (3.8)	90.7 (0.2)	79.3 (1.2)	91.5 (0.6)	91.8 (0.8)	88.0 (0.6)	88.3 (0.5)	87.2 (0.5)

Treatment composition based on FW:YT:WC wet volume ratio: M1—1:0:0, M2—0:1:0, M3—0:0:1, M4—0.5:0.5:0, M5—0.5:0:0.5, M6—0:0.5:0.5, TM1—0.33:0.33:0.33, TM2—0.33:0.33:0.33, TM3—0.33:0.33:0.33. All values in parenthesis are the standard deviation (n = 3). *FAS* free air space, *TC* total carbon, *TKN* total Kjeldahl nitrogen, *OM* organic matter, *DM* dry matter their dry mass. Formulas M1 (FW) and M4 (FW and YT) lost the most dry mass at 67.5 and 66.9 %, respectively, followed by M5 (FW and WC) at 42.6 % and then TM3 (FW, YT and WC) at 37.6 %. All other experimental formulas, namely M2 (YT), M3 (WC) and M6 (YT and WC), lost less than 19 % of their dry mass but gained moisture as opposed to the other formulas. Losses in TC and OM were highly proportional to each other by a factor of 1.09 ($R^2 = 0.99$), but not proportional to losses in dry mass ($R^2 < 0.25$), indicating that a non negligible mass of elements was lost through the leachate. Finally, COD losses were proportional to TC and OM losses by a factor of 1.07 and 0.98, respectively; for example, for each 1 kg loss of OM, COD losses represented 0.98 kg. The losses of TC and OM were proportional to the soluble organics content of the formula, with those rich in FW losing the most and those rich in WC losing the least.

Losses in TKN were inversely proportional to the original formula C:N ratio ($R^2 = -0.69$), namely highest for M1 (FW) and M4 (FW and YT), followed by M2 (YT), M5 (FW and WC) and M6 (YT and WC). Nevertheless, losses in TKN were not highly correlated with losses in dry mass or OM and TC. More likely, formulas with a low C:N ratio loss more nitrogen because of an excess versus the carbon available for the generation of microbial biomass. All formulas tended towards a final C:N of 10–17, except for those with 100 % WC, where their C:N remained above 40, because WC offers a high level of C but with a limited biodegradability.

Experimental Formula Oxygen Uptake

Before analyzing the O_2 uptake rate (OUR) and cumulative O_2 uptake (COU) of all experimental formulas, the reproducibility of the respirometric procedure was verified by analyzing the results obtained with the triplicate tertiary formulas (FW:YT:WC = 0.33:0.33:0.33) with their characteristics presented in Table 2. The physico-chemical characteristics of the 3 TM formulas prepared at a different time were not statistically different ($p > 0.05$), despite slight differences resulting from the heterogeneity of the raw experimental materials. Comparing results among the 3 TM tested (Fig. 3), the coefficient of variation (CV) for the peak OUR and the 32 day COU were 1.5 and 7.2 %, respectively, where a value below 10 is considered acceptable. As compared to formulas TM1 and TM3, formula TM2 produced a slightly higher OUR peak occurring 1.0 day earlier. This difference can be explained by a number of factors, including: the test temperature for TM2 slightly higher at 40.4 °C (±2.2), as compared to 39.5 °C (±2.0) and 39.0 °C (±2.0) for TM1 and TM3 respectively, experimental variation and; the higher ($p < 0.05$) DM of

Table 3 Characteristics of the experimental formulas after 32 days of respirometry

Characteristics	Mixtures								
	M1	M2	M3	M4	M5	M6	TM1	TM2	TM3
Wet mass (kg)	1.0	0.8	2.1	1.1	2.0	1.8	2.5	2.2	2.2
Dry mass (kg)	0.2	0.2	1.1	0.2	0.7	0.8	0.7	0.6	0.59
DM (%)	20.0	25.0	52.0	19.0	35.0	45.0	28.0	27.0	27.0
Dry mass loss (% of initial dm)	67.5	19.0	0.7	66.9	42.6	5.0	37.0	34.2	37.6
Wet mass loss (% of initial wet mass)	70.6	−86.1[a]	−83.8[a]	64.2	35.0	−77.3[a]	17.0	13.2	15.1
TC (% dm)	31.7 (0.5)	28.1 (0.2)	46.1 (0.5)	29.6 (0.3)	20.7 (0.5)	33.1 (0.3)	31.7 (0.2)	27.5 (0.3)	28.2 (0.4)
TC loss (% of initial TC)	78.6	51.2	0.9	79.8	74.8	29.9	56.4	61.5	56.5
TKN (g/kg dm)	19.0 (0.2)	20.7 (0.1)	9.6 (0.03)	27.4 (0.3)	12.2 (0.3)	17.6 (0.1)	26.3 (0.4)	21.4 (0.1)	23.7 (0.02)
TKN loss (% of initial TKN)	73.9	33.0	0	62.5	49.5	39.1	0	15	0
C:N ratio	16.7	13.6	47.0	10.8	17.0	18.8	12.0	12.8	12.0
COD (g/kg dm)	818 (16.4)	727 (9.4)	–	730 (11.0)	326 (24.1)	977 (17.6)	781 (15.6)	659 12.5)	732 (2.2)
COD loss (% of initial COD)	80.6	55.6	–	82.4	84.4	23.1	64.1	66.4	59.0
OM (% dm)	41.6 (0.3)	55.0 (0.1)	–	47.5 (0.2)	23.6 (0.5)	63.3 (0.2)	57.3 (0.5)	45.4 (0.7)	49.7 (0.8)
OM loss (% of initial OM)	83.5	35.9	–	80.1	85.2	34.5	59.0	66.2	64.5

Formulas based on FW:YT:WC wet volume ratio: *M1*—1:0:0, M2—0:1:0, M3—0:0:1, M4—0.5:0.5:0, M5—0.5:0:0.5, M6—0:0.5:0.5, TM1—0.33:0.33:0.33, TM2—0.33:0.33:0.33, TM3—0.33:0.33:0.33. All values in parenthesis are the standard deviation for n = 3. [a]Water gain from saturated aerated air, *TC* total carbon, *TKN* total Kjeldahl nitrogen, *OM* organic matter, *dm* dry matter

TM2 at 38.1 % as compared to 36.2 and 36.8 % for TM1 and TM3 respectively [24].

Considering that the 3 series of tests did not differ significantly, Fig. 4 compares the average OUR values for each formula. On day 32 and with an OUR under 7.0 mol/h/kg dm, all formulas were considered decomposed and stable. The highest OUR peak of 145 mol/h/kg dm was obtained with formula M4 (FW and YT), followed by formula TM (FW, YT and WC) at 115 mol/h/kg dm. The M1 (FW) formula was likely too wet to yield one of the highest peak OUR values, despite its high soluble organics content. Furthermore, the neutral pH and high DM of YT helped produce higher peak OUR values when mixed with FW. Whereas YT and FW contributed to increasing the formula peak OUR value, WC dropped the peak OUR value under 5 mol/h/kg dm at over 50 % wet volume. All 3 of the formulas with at least 50 % WC offered a C:N ratio above 30 with M3 and M6 offering at least 80 % DM.

The time to peak OUR depended on the formula, where: the DM influenced its heat capacity, and; the soluble organics content and C:N ratio enhanced microbial activity and heat generation. In terms of time to peak OUR, a high C:N ratio corrected the negative effect of a DM outside the recommended range. Nevertheless, an early peak OUR did not necessarily correspond to a higher peak OUR. The shortest time to peak OUR of 1.0 day was reached by formula M2 (YT) because of its high DM of 60 % accompanied by a low C:N ratio of 18.5 and an intermediate soluble organics content. In comparison, the high DM of M2 (YT) likely limited its peak OUR value. The next formula to reach a peak OUR at 3 days was TM (FW, YT and WC) because of its intermediate DM and C:N ratio of 37 % and 28, respectively, and its intermediate soluble organics content. Next at 5 days, formula M4 (FW and YT) reached its peak OUR with a DM of 25 % and a C:N ratio of 20; this formula reached the highest peak OUR value because of its high soluble organics content and appropriate DM, as compared to M1 (FW). Finally at 6 days, M1 (FW) with a respective DM and C:N of 21.3 % and 20.4, and formula M5 (FW and WC) with a respective DM and C:N of 39 % and 32, both reached their peak OUR. Nevertheless, formula M1 produced a higher peak OUR value than that of M5, because of its higher soluble organics content.

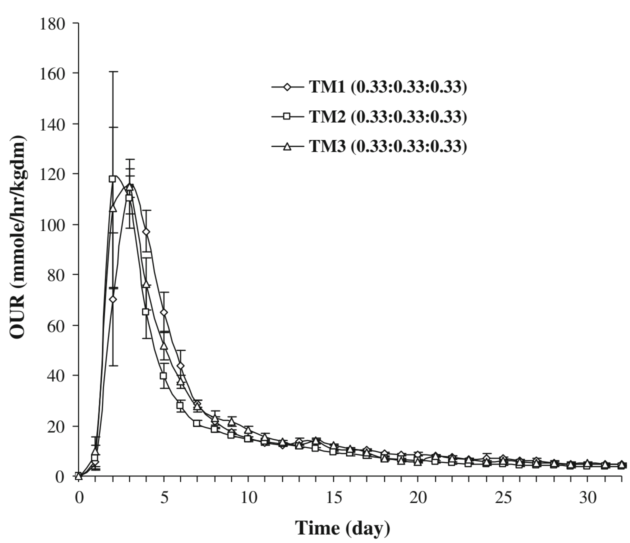

Fig. 3 Oxygen uptake rate (OUR) profile illustrating the repeatability of trial TM (average of trials TM1, TM2 and TM3) with a FW:YT:WC ratio of 0.33:0.33:0.33, based on their wet volume. *Y bars*—standard deviation

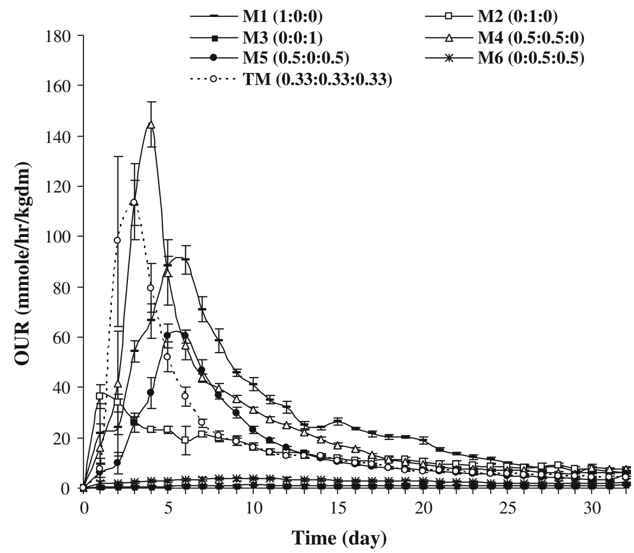

Fig. 4 Oxygen uptake rate (OUR) profile for the formulas of organic waste. *Note*: all formulas were formulated from the wet volume of food waste (FW), yard trimmings (YT) and wood chips (WC) (FW:YT:WC). Each component ranged from 0 to 1. TM—average of triplicate testing for 0.33:0.33:0.33 FW:YT:WC, namely TM1, TM2 and TM3. *Y bars*—standard deviation

The cumulative O_2 uptake (COU) curves over 32 days are illustrated in Fig. 5. The highest COU was achieved by formula M4 (FW and YT) followed by M1 (FW) and TM (FW, YT and WC), and then M5 (FW and WC) and M2 (YT). Loss of OM was exponentially proportional to COU ($R^2 = 0.88$). Formula M4 (FW and YT) produced the highest COU as a result of its appropriate DM of 25 %, the neutral pH effect of YT and its low C:N of 18.6. Formulas M3 (WC) and M6 (YT and WC) produced limited amounts of COU, because of their DM exceeding 80 %. The COU ranking respected that of the peak OUR values, except for the reverse order of formula M1 (FW) as compared to TM (FW, YT and WC), because of its higher soluble organics content.

Formula Response Modelling and Profile

Multivariate linear regression was used to decipher the association between peak OUR (dependent variable) and

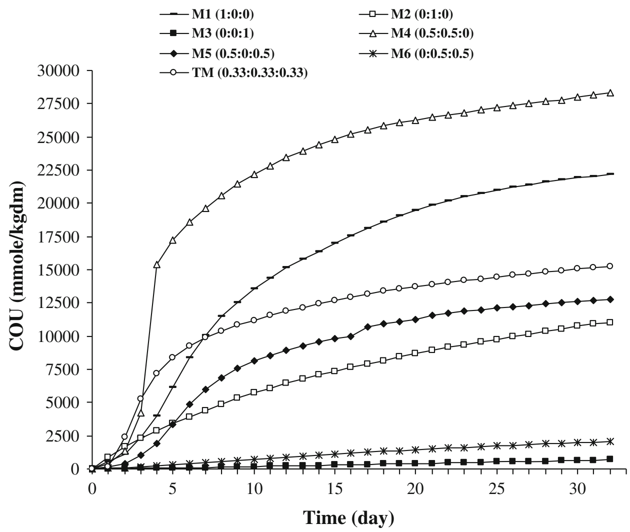

Fig. 5 Cumulative oxygen uptake (COU) for formulas of food waste (FW), yard trimmings (YT) and wood chips (WC) during 32 days of respiratory. TM—average of triplicate testing for a 0.33:0.33:0.33 FW:YT:WC, namely TM1, TM2 and TM3

Table 4 Regression coefficients and significance for peak OUR model

Formula component	Regression coefficient	Coefficient estimation	p value
FW	C_1	91	0.0004
YT	C_2	36	0.0023
WC	C_3	1.4	0.5004
FW and YT interaction	C_{12}	326	0.0007
FW and WC interaction	C_{13}	59.2	0.0196
YT and WC interaction	C_{23}	−58.8	0.0198
FW, YT and WC interaction	C_{123}	995.32	0.0021

OUR oxygen uptake rate, *FW* food waste, *YT* yard trimmings, *WC* wood chips

formula component, FW, YT and WC (independent variable). The significance of the linear interaction coefficients of Eq. (3) was proportional to the soluble organics content, (Table 4) with FW exerting a highly significant effect ($p = 0.0004$), followed by YT ($p = 0.002$) and then WC with no significant effect ($p = 0.50$). The model interaction coefficient for FW/YT produced a highly significant effect ($p = 0.0007$) while that for FW/WC and YT/WC produced a significant effect ($p = 0.02$). The interaction between all 3 components, FW/YT/WC was highly significant ($p < 0.002$), indicating a WC contribution in terms of formula structure and aeration, with FW and YT providing soluble organics and a more neutral pH, respectively, besides the effect on DM.

The model was successfully tested as the measured and estimated peak OUR for all experimental formulas (Fig. 6) produced a high coefficient of determination ($R^2 = 0.99$). Accordingly, Eq. (3) was used to predict peak OUR as a function of formula FW, YT and WC wet volume ratio (Fig. 7). The model predicted the highest peak OUR at 160 mol O_2/h for a FW:YT:WC fraction of 0.6:0.4:0. Thus, YT as bulking agent is sufficient and WC is not essential. Formulas with a FW wet volume fraction approaching 1.0 still produce a high peak OUR of 90 mol O_2/h, while formulas with a YT or WC fraction approaching 1.0 produce respectively, low peak OUR of 40 and less than 20 mol O_2/h. Accordingly, FW needs a bulking agent to produce a high peak OUR, because of its low DM of 21.3 % and acid pH; YT enhances peak OUR when mixed with FW, because of its higher DM at 60.4 % and its neutral pH. Both FW and YT offer a low C:N ratio enhancing microbial activity, but also increasing potential nitrogen losses.

Conclusions

Composed mainly of food waste (FW) and yard trimmings (YT), organics represent one of the major fractions of the municipal solid waste mainstream. Composting constitutes a practical recycling alternative to landfills for this fraction. As compared to centralized composting facilities, home composting is identified as less costly reducing the need for handling, transportation, labour and infra-structures. Nevertheless, optimal home composting formulas have not been investigated, thus setting the objective of this study. Formula optimization was based on respirometry or oxygen uptake rate (OUR) and cumulative oxygen uptake (COU). A higher peak OUR was associated with a more active microbial decomposition process and accordingly, a faster process with higher stabilizing temperatures, while COU was associated with a higher loss of dry mass.

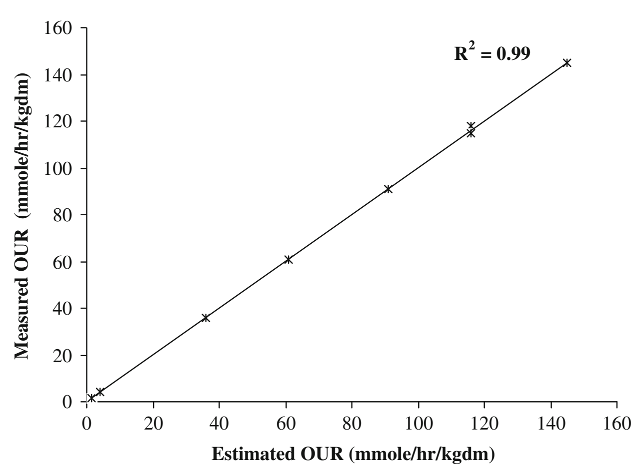

Fig. 6 Relationship between measured and estimated oxygen uptake rate (OUR)

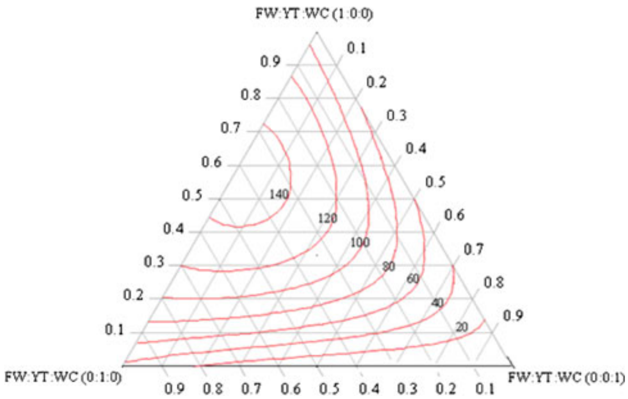

Fig. 7 Surface contours for estimated response in oxygen consumption rate for the various formulas of food waste (FW), yard trimmings (YT) and wood chips (WC) expressed in mmol/h/kg dm. The *left axis* gives FW, the *right axis* gives WC and the *bottom axis* gives YT

Using 3 experimental materials, FW, YT and wood chips (WC), this study demonstrated that formula components significantly ($p < 0.01$) influenced peak OUR and thus microbial activity. Among the tested formulas, the binary formula of FW and YT, at a fraction of 0.5:0.5, demonstrated the highest OUR of 145 mol/h/kg dm and COU of 28.4 mol/kg dm followed by the tertiary formula (FW, YT, WC at a fraction of 0.33:0.33:0.33) with a peak OUR of 115.6 mol/h/kg dm and COU of 15.3 mol/kg dm. The pure formulas of YT and WC were too dry to support an active microbial activity. The regression model demonstrated that the best home composter formula consists of a FW:YT wet volumetric fraction of 0.6:0.4, and that WC is not necessary when YT is available.

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