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Compost mixture influence of interactive physical parameters on microbial kinetics and substrate fractionation

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Abstract

Composting is a feasible biological treatment for the recycling of wastewater sludge as a soil amendment. The process can be optimized by selecting an initial compost recipe with physical properties that enhance microbial activity. The present study measured the microbial O_2 uptake rate (OUR) in 16 sludge and wood residue mixtures to estimate the kinetics parameters of maximum growth rate μ_m and rate of organic matter hydrolysis K_h, as well as the initial biodegradable organic matter fractions present. The starting mixtures consisted of a wide range of moisture content (MC), waste to bulking agent (BA) ratio (W/BA ratio) and BA particle size, which were placed in a laboratory respirometry apparatus to measure their OUR over 4 weeks. A microbial model based on the activated sludge process was used to calculate the kinetic parameters and was found to adequately reproduced OUR curves over time, except for the lag phase and peak OUR, which was not represented and generally over-estimated, respectively. The maximum growth rate μ_m, was found to have a quadratic relationship with MC and a negative association with BA particle size. As a result, increasing MC up to 50 % and using a smaller BA particle size of 8-12 mm was seen to maximize μ_m. The rate of hydrolysis K_h was found to have a linear association with both MC and BA particle size. The model also estimated the initial readily biodegradable organic matter fraction, MB_0, and the slower biodegradable matter requiring hydrolysis, MH_0. The sum of MB_0 and MH_0 was associated with MC, W/BA ratio and the interaction between these two parameters, suggesting that O_2 availability was a key factor in determining the value of these two fractions. The study reinforced the idea that optimization of the physical characteristics of a compost mixture requires a holistic approach.

Key words: composting, microbial kinetics, respirometry, sludge, wood residues.

1. Introduction

Composting the sludge produced by treatment plants receiving mainly domestic or food processing wastewaters is a sustainable method of recycling carbon with minimum greenhouse gas production (Amlinger et al., 2008). Composting relies mostly on the ability of microorganisms to biodegrade and stabilise the organic waste, to destroy pathogens and produce an esthetically acceptable soil conditioner (Insam and de Bertoldi, 2007; Metcalf and Eddy, 2003). Increasing urbanization and industrialization in cities resulted in the production of more sludge waste requiring disposal or anaerobic digestion (Adhikari, 2005). Otherwise, this sludge waste is landfilled where it is mostly transformed into CH_4 because of ambient anaerobic conditions (Rashmussen and Khalil, 1984). At the landfill site, 45 to 58 % of organic waste on a dry mass basis is transformed into CH_4, which can be captured at a cost to produce energy (Solid Waste Landfill Guidance, 1999).

Composting consists of 3 to 4 weeks of biodegradation in the active phase, followed by several months of maturation in the curing phase (Gupta and Garg, 2008). As opposed to the curing phase which stabilizes the more resistant compounds (Haug, 1993), the microbial activity of the active phase can be manipulated and optimized through a better understanding of the interaction between the physical parameters. For the biodegradation and stabilization of compost mixtures, Mohajer et al. (2009) demonstrated the interaction on O_2 uptake rate (OUR) of physical parameters, namely moisture content (MC), bulking agent (BA) particle size distribution and BA to waste (W) ratio.

The interactive effect of physical parameters on compost decomposition as measured by Mohajer et al. (2009) can be further quantified by estimating microbial degradation parameters. Such microbial parameters can be estimated by assuming that the compost mixture OUR is similar to that of wastewater activated sludge systems decomposing BOD. The traditional approach to respirometric modeling associates changes in microbial O_2 consumption with the growth and decay of the biomass (Spanjers et al., 1998). Past literature has presented models estimating the influence on composting of parameters such as temperature (Haug, 1993; Tremier et al., 2005; Richard and Walker, 2006), moisture content (MC) (Richard et al., 2002) and aeration rate (Richard et al., 2006; de Guardia et al., 2008). Certain physical parameters, such as MC and BA properties however, have been shown to be particularly important due to their strong interdependent effect on microbial O_2 uptake (Diaz et al., 2007; Mohajer et al., 2009).

Tremier et al. (2005) developed a kinetics model describing microbial growth rate and sludge waste biodegradation. Based on the activate sludge model, the Tremier model estimates kinetic parameters through the linear transformation of O_2 consumption rate measured during the decomposition of organic matter by a heterotrophic biomass. The strength of the Tremier model lies in the fact that it considers the organic matter as split into three different fractions, mainly, the readily biodegradable fraction (*MB*), the biodegradable fraction requiring hydrolysis (*MH*) and the inert fraction (*IM*). Only a few composting models have included the hydrolysis process (Hamelers, 1993; Liwarska-Bizukojc et al., 2002), even though it was shown to be rate-limiting (Veeken and Hamelers, 1999; Sole-Mauri et al., 2007). Although the Tremier model does not include all components and variables affecting composting, its strength lies in its simplicity and its inclusion of a hydrolysis step.

Accordingly and for compost mixtures, the objective of this study was to estimate the microbial kinetic parameters and organic matter biodegradation dynamics as a function of the interaction between the physical properties of moisture content (MC), bulking agent to waste ratio (BA/W ratio on a dry basis) and BA particle size. Consisting of slaughter house wastewater sludge and wood residues recycled from a composting operation, the experimental compost mixtures offered a wide range of combinations in term of physical properties. For individual compost mixtures, the O_2 uptake rate (OUR) was measured during 24 days using a respirometry apparatus (Mohajer et al., 2009). With the OUR data, the Tremier model was used to estimate the maximum microbial growth rate, μ_m and then the organic matter degradation parameters, namely organic matter hydrolysis rate, K_h, and the initial fractions of readily degradable organic matter, $MB_{0,}$ and that requiring hydrolysis, MH_0.

2. Material and Methods

2.1. Conceptual approach of the model

The model developed by Tremier et al. (2005) assumes that the substrate has three phases: a dry solid phase, an aqueous phase and a porous phase. Within this three phase matrix consisting of the BA and sludge mixture, the organic matter is assumed to offer three different initial fractions each with a specific biodegradation rate: the readily biodegradable faction, MB_0, the fraction requiring hydrolysis, MH_0, and that which is inert or not degraded, *MI*.

The first fraction, MB_0, is already soluble and is readily used as a source of carbon and energy by microorganisms. As a carbon source and depending on the biomass growth yield *Y*, part of *MB* is transformed to give new biomass. The microbial population grows as a function of available *MB* and its maximum growth rate and death coefficient:

$$dX/dt = X_t \times \{ \mu_m \times MB_t/(K_b + MB_t) - b \} \quad (1)$$

where X_t is the biomass population in mmol O_2 (kg dry matter)$^{-1}$; t is time in h^{-1}; μ_m is the maximum growth rate of the biomass in h^{-1}; MB_t is the mass of readily biodegradable organic matter at time t in mmol O_2 (kg dry matter)$^{-1}$; K_b is the saturation constant for MB set at 3 mmol O_2 (kg dry matter) $^{-1}$; and b is the death coefficient of the biomass set at 0.05 h^{-1} (Tremier et al., 2005).

The energy needed for biomass growth is supplied through the oxidation of a fraction of MB and the dead biomass expressed as (1-Y) MB and (1- f) X_t. Thus, the O_2 uptake rate (OUR) can be expressed as:

$$R_{O2}(t) = X_t \times \{ (1-Y) / Y \times \mu_m \times MB_t/(K_b + MB_t) + b \times (1-f) \} \quad (2)$$

where $R_{O2}(t)$ is the O_2 uptake rate (OUR) at time t in mmol O_2 (kg of dry matter - h)$^{-1}$; Y is the yield coefficient of the biomass growth set at 0.68 (dimensionless); f is the fraction of dead biomass contributing to MI, dimensionless, and MI is the fraction of inert organic matter in mmolO_2 (kg of dry matter)$^{-1}$.

The second biodegradable fraction labeled MH supplies MB to the microorganisms through enzymatic hydrolysis:

$$dMH/dt = X_t \times \{ -K_h \times MH_t/X_t / (MH_t/X_t + K_{mh}) \} \quad (3)$$

where MH_t is the fraction of solid or soluble organic matter at time t which requires hydrolysis to become readily biodegradable in mmol O_2 (kg of dry matter)$^{-}$1 ; K_h is the rate of hydrolysis for the fraction MH in h^{-1} and K_{mh} is the hydrolysis saturation constant for the ratio MH_t/X_t set at 6.5 (dimensionless).

The resulting mass balance for the readily biodegradable MB fraction can thus be expressed as:

$$dMB/dt = X_t \times \{ - 1/Y \times \mu_m \times MB_t/(K_b + MB_t) + K_h \times (MH_t/X_t) / (MH_t/X_t + K_{mh}) \} \quad (4)$$

The hydrolysis reaction is initiated from the very beginning but becomes the rate limiting process after the peak OUR, as microorganisms are left with the remaining complex organic macromolecules requiring hydrolysis and governed by the rate K_h. Resistant organic matter, such as cellulose and lignin accumulated from the biodegradation of the two first fractions, are partly transformed into the third inert fraction *MI*. The degradation of the first two fractions also leads to the accumulation of dead biomass which, through degradation, is partly accumulated as inert matter, *MI*. The fraction of dead biomass contributing to *MI* is defined by the coefficient *f* with a value of 0.2 (Tremier et al., 2005).

2.2 Parameter Estimation

Equations 1 to 4 were used to estimate the kinetic parameters μ_m, K_h and X_0, and the organic matter fractions of MB_0 and MH_0 at time zero (Table 1). The dynamic biological model was fitted to the experimental OUR recorded through respirometry. For each trial, the output parameters of the model were calibrated to the experimental OUR using an optimization program designed by Tremier et al. (2005) for the SCILAB software (INRIA, France) based on a least squared method. Default values for *Y, f, b,* K_b, K_{mh} were chosen based on published literature corresponding to 0.68 (dimensionless), 0.2 (dimensionless), 0.05 h^{-1}, 3 mmol O_2 (kg dry matter)$^{-1}$ and 6.5 (dimensionless), respectively (Tremier et al., 2005). The value of the kinetic parameters μ_m and K_h and for X_0, MB_0 and MH_0 were optimized through fitting using linearization methods performed on the exponential rise and subsequent fall of the experimental OUR curves obtained from respirometry. The linearization method corresponds to a simplified way of interpreting the respirometry curve and the values were derived from an identification procedure based on structural identifiable procedures (Dochain et al., 1995; Sperandio and Paul, 2000).

2.3. Substrate Material and chemical characterization

The experimental materials consisted of sewage sludge from the wastewater treatment facility of a slaughter house and as BA, green waste or twigs and branches recycled from a composting process. For consistency, a large sludge sample obtained prior to the trial was split into 10 kg sub samples and stored until use at -20°C. Table 1 characterizes the experimental materials.

The experimental materials were analyzed for dry matter (DM), organic matter (OM), total organic carbon (TOC), chemical O_2 demand (COD) and total Kjeldahl nitrogen (TKN) prior to the start of the experiment. The DM was measured by drying the wet samples at 80°C to constant weight. A higher temperature was avoided to prevent the combustion of this type of sample during drying. The OM content was measured by burning the dried ground samples at 550°C for 4 h using the standard method NF U 44-160 (Afnor, 1985). The TOC was measured by oxidizing the dried ground samples to CO_2 and using infrared spectrometry (SKALAR device) to measure CO_2 production according to the standardized method NF-EN-13137 (Afnor, 2001a). The sample COD was determined by the oxidation of 50 mg of dried ground sample using potassium dichromate, according to an adaptation of the standard method described in the norm NF T 90-101 (Afnor, 2001b) for powdered samples. The TKN content was quantified on 50 mg of dried ground sample by mineralization with a strong acid medium (98% sulphuric acid), followed by steam distillation and titrimetric determination, an adaptation of the standard method NF ISO 11261 (Afnor, 1995) for powdered samples.

2.4. Respirometric Measurement Method

Mohajer et al. (2009) describes the respirometric apparatus used in this study to measure OUR resulting from the biodegradation of the waste mixtures (Figure 1). It consisted of six cylindrical 10 L airtight reactors made of stainless-steel and submersed in a water bath controlled at 40 °C, a temperature was found to produce optimal biodegradation conditions (Tremier et al., 2005). Inside the reactor, the substrate material was placed on a 3 mm mesh grid located 70 mm above the cell bottom forming a plenum receiving 65 L h^{-1} of air via a glass diffuser. As past studies have shown that an intermittent air supply can lead to O_2 limitations (Paletski and Young, 1995), a continuous air flow was supplied. Homogenous O_2 diffusion for the trials was ensured by re-circulating part of the exhaust air back into the cells. The entering and exhaust air streams were monitored for O_2 content using a paramagnetic O_2 gas analyser (MAIHAK Technology, Nimburger, Germany).

To solely test the effect of the experimental physical factors on microbial activity, the apparatus controlled other environmental factors. Along with that of the sample, the temperature of the inlet air was preheated at 40 °C using a copper serpentine 10 mm in diameter, 2 mm in thickness and 2 m in length submerged in the water-bath. The temperature of the sample was monitored by means of a Pt100 temperature probe (OMNI Instruments, UK) inserted in the centre of the cell. The inflowing air was saturated with moisture by bubbling through two water-filled glass bottles immersed in the water-bath. Moisture condensing in the exhaust air was collected in beakers above the water-bath to prevent its return into the sample cells. Once the experiment began, the samples were left inside the respirometric cells until their OUR dropped to a low constant value, usually corresponding to four weeks.

2.5. Experimental design and statistical analysis

The 16 experimental mixtures were created by combining low, intermediate and high values of the three physical parameters namely MC, W/BA ratio and BA particle size (Table 2), determined using a response surface method experimental design. Water or dried sludge were mixed with the appropriate amount of BA to obtain MCs of 20, 30, 45, 60 and 70 %, although actual experimentally recorded MC varied slightly (Table 2). The waste mixtures were manually mixed with BA to create W/BA ratios at 1/9.2, 1/7.9, 1/6, 1/4.1 and 1/2.1 on a dry basis. Finally, different BA particle sizes of 8 to12 mm, 12 to 20 mm, 20 to 30 mm, 30 to 40 mm and over 40 mm were achieved by sieving through rotary screens. The C:N ratio of all experimental recipes ranged between 10 and 22, which are acceptable for sludge composting (Table 2).

A 3 kg (wet mass) sample of each mixture was placed in individual cells to prevent BA breakage and to minimize mixture compaction. All O_2 uptake rates (OUR) were expressed on the basis of initial mixture dry mass. Six compost recipes were tested at any one time. In total, 16 compost recipes were tested without duplication because of the wide range of incremental levels used in the combinations selected.

Using the observed experimental respirometric data, univariate linear regression was first performed to delineate the marginal relationships of the measured MC, W/BA ratio and the mean BA particle size in each range, with each of μ_m, K_h, MB_0 and MH_0. Multivariate linear regression was subsequently performed to decipher the associations between the physical characteristics of each treatment including their interactions, upon each of the kinetic parameters and substrate matter fractions after 28 days of aeration, using the statistical software package Stata® (Statacorp LP, Texas, USA). The regression model was:

$$E[Y] = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \beta_3\chi_3 + \beta_{12}\chi_1\chi_2 + \beta_{13}\chi_1\chi_3 + \beta_{23}\chi_2\chi_3 + \beta_{11}\chi_1^2 + \beta_{22}\chi_2^2 + \beta_{33}\chi_3^2 \quad (5)$$

where Y is the outcome of interest; β_0 is the intercept; β_1, β_2, β_3 are the linear coefficients; β_{12}, β_{13}, β_{23} are the interaction coefficients; β_{11}, β_{22}, β_{33} are the quadratic coefficients; χ_1 is the MC in %; χ_2 is the BA particle size in mm, dimensionless, and; χ_3 is the W/BA ratio.

Analysis of variance (ANOVA) determined the significance of the models using the F-Test, at a confidence level of 90% ($p < 0.1$). Moreover, the significance of each regression model parameter (variable or interaction) was determined using a Student Test at a confidence level of 75% ($p < 0.25$). The regression coefficient R^2 measured the global fit of the regression model with the experimental data and the adjustment of the models was considered acceptable for R^2 greater than 55 %.

3. Results

3.1 Model validation

Figures 2 and 3 illustrate the OUR over time for experimental mixtures 4 and 9, respectively, obtained through experimental trials and model simulations using Scilab. Mixtures 4 and 9 offered the largest and smallest variations between the experimental and simulation curve, respectively, obtained after optimization of the cycles to improve the fit of the simulation curve. For all experimental mixtures, the general OUR curve was reproduced, except for the peak which was generally slightly overestimated. Considering that the area under the curve is used to estimate MB_0 , this model overestimation introduces an error of 5 % at the very most. Furthermore, the model accurately reflected the exponential rise in OUR determining mainly the maximum growth rate μ_m of the microbial population. The simulations however, lacked the ability to reproduce the brief lag phase observed at the beginning of the trials where microorganisms were acclimating to mixture conditions. Nonetheless, the relatively short lag phase of less than 12 hours did not interfere with the subsequent exponential rise in OUR, resulting in similar experimental and simulation curves.

After the peak, the model simulation correlated closely with the subsequent and gradual drop in sample OUR. This period is presumed to correspond mainly to the biodegradation of the more complex organic fraction requiring hydrolysis, MH_0, resulting in a drop in OUR. As less biodegradable matter remains accessible to the microbes, the OUR recesses to lower levels (Tremier et al., 2005).

3.3. Influence of physical parameters on microbial kinetic coefficients

The experimental OUR curves were used to estimate the maximum growth rate and hydrolysis kinetics in each of the 16 experimental recipes (Table 3). The maximum growth rate μ_m varied from 0.07 h^{-1} achieved in mixture 6 (MC of 30 %, W/BA ratio of 1/7.9 and BA particle size of 30-40 mm), to 0.20 h^{-1} in mixture 3 (MC of 52 %, W/BA ratio of 1/6 and BA particle size of 8-12 mm). The average μ_m for all 16 experimental mixtures was 0.106 h^{-1}. These values are somewhat lower than that found in other studies, perhaps due to the characteristic of the sludge waste. Tremier et al. (2005) found ranges between 0.13 and 0.34 h^{-1} using sewage sludge and pine bark in a 1:1 wet mass ratio biodegraded under temperatures of 20 to 70 °C. Activated sludge models suggest a typical value of 0.25 h^{-1} at 20 °C, but they pertain to the raw volatile solids contained in municipal wastewaters. Kaiser (1996) suggested a μ_m value of 0.2 h^{-1} at 40 °C for the biodegradation modelling of vegetable substrates during composting.

Through regression analysis, the maximum growth rate, μ_m, was found to be significantly affected by MC, via a quadratic relationship, and BA particle size (p<0.05) (R^2 = 0.63):

$$\mu_m = 0.1126 + 0.0006 \times \chi_1 - 0.0018 \times \chi_1^2 - 0.0018 \times \chi_2 + 0.0001\chi_2^2 \quad (6)$$

for χ_1= (MC - 45), %; χ_2= (BA particle size – 25), mm

The nature of the quadratic association between MC and growth rate was such that increased moisture levels up to 50 % were associated with larger μ_m (Figure 4). A reduction in μ_m at levels higher than 50 %, however, resulted in MC reducing the free air space and impeding O_2 availability. The negative association between BA particle size and μ_m, on the other hand, reflected the ability of the biomass to maximize surface area attachment and waste biodegradation. Found previously to affect microbial OUR (Mohajer et al., 2009), W/BA ratio and its interactions with the other physical parameters did not have a significant impact on μ_m as a result of the inoculation effect of the sludge and the BA. The sludge/BA mixture probably contained a high initial microbial population that rapidly expanded upon exposure to aeration, reducing the potential impact that an optimal physical matrix could provide on microbial activity.

Averaged for all 16 experimental recipes, the estimated rate of hydrolysis, K_h, had a mean value of 0.098 h^{-1} over a range of 0.081 h^{-1} in mixture 11 (MC of 52 %, W/BA ratio of 1/6 and BA particle sizes of over 40 mm) to 0.12 h^{-1} in mixture 8 (MC of 62 %, W/BA ratio of 1/4.1 and BA particle sizes of 12-20 mm). These values were slightly higher than those suggested by Sole-Mauri et al. (2007), which ranged from 0.007 to 0.04 h^{-1}, depending on the substrate, but were less than those reported by Tremier et al. (2005) at 0.1 to 0.2 h^{-1} depending on the temperature. The rate of hydrolysis was found to be significantly associated to MC and BA particle size (p<0.05) but also influenced by the interaction between W/BA ratio and BA particle size (R^2 = 0.56):

$$K_h = 0.0986 + 0.0005 \times \chi_1 - 0.0008 \times \chi_2 - 0.0101 \times \chi_2\chi_3 \quad (7)$$

for χ_1 = (MC - 45), %; χ_2 = (BA particle size – 25), mm; χ_3 = (W/BA ratio -0.167), dimensionless.

A higher MC and smaller BA particle size value tended to increase K_h. Accordingly, the hydrolysis reaction is favoured by an increasing MC and a large specific surface provided by smaller BA particle size (Figure 5). The importance of a small BA particle size is underlined through the interaction with W/BA. Hence, if the quantity of sludge in the mixture is increased, BA particle size has to decrease not to limit the hydrolysis kinetics.

3.4 Influence of physical parameters on the biodegradable organic fraction

The model estimated the readily biodegradable organic matter fraction, MB_0, and the fraction requiring hydrolysis, MH_0 (Table 1), available for microorganisms in the studied experimental conditions. The MB_0 fraction ranged from a low of 475 mmol O_2 (kg dry matter)$^{-1}$ in mixture 6 with a relatively large BA particle size of 30-40 mm and a low W/BA ratio and MC of 1/7.9 and 30 %, respectively, to a high of 2 085 mmol O_2 (kg dry matter)$^{-1}$ for mixture 3 with a smaller particle size of 8-12 mm, higher W/BA ratio of 1/6 and an optimal MC of 50 %. A minimum MH_0 fraction of 7 950 mmol O_2 (kg dry matter)$^{-1}$ was reached for mixture 1 with the lowest W/BA ratio of 1/9.2 and an intermediate value of BA particle size of 20-30mm. The maximum MH_0 concentration of 18 160 mmol O_2 (kg dry matter)$^{-1}$ was reached with mixture 5 with a large W/BA ratio of 1/6 and a high of MC of 68 %.

The MB_0 fraction was mainly influenced by BA particle size, and the interaction between MC and W/BA ratio ($p<0.05$). To a less extent, it was also influenced by individual effects of W/BA ratio ($p<0.15$) and MC ($p<0.25$) ($R^2 = 0.64$):

$$MB_0 = 1182 + 6.99 \times \chi_1 - 24.20 \times \chi_2 + 1861 \times \chi_3 - 275.42 \times \chi_1\chi_3 \quad (8)$$

for χ_1 = (MC-45), %; χ_2 = (BA particle size – 25), mm; χ_3 = (W/BA ratio -0.167), dimensionless.

Predictably, less BA with a smaller particle size increased MB_0 since the BA is less biodegradable than the sludge. Increasing MC probably allows microorganisms to better reach the available MB_0. MC and W/BA ratio impacted available MB_0 through a negative interactive effect where an increase in either parameter had a decreasing effect. This negative crossed effect of MC and W/BA resulted from physical restrictions on the accessibility of the organic matter and oxygen to the microorganisms. Indeed, with high moisture and a high quantity of sludge versus BA, the porosity of the medium can be limited, consequently affecting the aeration of the microorganisms. On the other hand, with low moisture and a low quantity of sludge versus BA, conditions for microorganisms activity are also limited.

The sum of MB_0 and MH_0 is equivalent to the total amount of organic matter biodegraded over the four weeks of respirometry. The total concentration ranged from a minimum of 8 912 mmol O_2 (kg dry matter)$^{-1}$ with mixture 1 with mid level values for both MC (42 %) and BA particle size (20-30 mm) and a low W/BA ratio (1/9.2). A maximum value of 19 585 mmol O_2 (kg dry matter)$^{-1}$ was obtained with mixture 5 with the highest MC (68 %) and mid-level values for both BA particle size (20-30 mm) and W/BA ratio (1/6). The biodegradable organic matter in the 16 mixtures comprised about 35 % of the total organic matter. As written concerning MB_0, the Tremier model was designed to evaluate the quantity of organic matter which can be oxidized under experimental conditions rather than the total potential biodegradable matter.

The sum of the MB_0 and MH_0 fractions were associated with MC, W/BA ratio and the interaction between MC and W/BA ratio (p<0.05) (R^2 = 0.59):

$$(MB_0 + MH_0) = 15211 + 114 \times \chi_1 + 14208 \times \chi_3 - 1769 \times \chi_1\chi_3 \quad (9)$$

for χ_1=(MC-45), %; χ_3=(W/BA ratio -0.167), dimensionless.

Increasing MC up to 50 % along with W/BA, increased the sum of MB_0 and MH_0 as a result of a more favourable water content and a higher sludge fraction. The negative interaction between the two parameters, however, altered the individual main effect (Figure 6). Coupled with larger W/BA ratio, MC above 50 % decreased the sum of MB_0 and MH_0, most likely due to lower O_2 diffusion as a result of less free-air-space. Thus, these results confirm the notion that the impact of MC and W/BA ratio in composting systems are interconnected, where the level of one parameter was important to interpret the impact of the other. For MC and the W/BA ratio exceeding 50 % and 1/4.1, respectively, Mohajer et al. (2009) also found a reduced OUR. The same conditions produced a reduction in the sum of MB_0 and MH_0 also as a result of less O_2 availability.

4. Conclusion

With compost mixture respirometry data, this study used the microbial Tremier model adapted from the activated sludge process to obtain microbial kinetic parameters describing maximum microbial growth rate μ_m, the rate of organic matter hydrolysis K_h and the initial fractions of organic matter being readily degradable MB_0 and requiring hydrolysis MH_0. These parameters were estimated for 16 experimental mixtures of sludge and wood residue offering various physical parameter combinations of moisture content (MC), waste to bulking agent ratio (W/BA ratio) and bulking agent (BA) particle size.

The model accurately simulated the OUR over time except for brief periods corresponding to the initial lag phase and peak. Differences in the estimated μ_m and K_h were shown to be mostly explained by the initial physical characteristics of the experimental mixtures and their interaction. The MC had a quadratic relationship with μ_m and a positive linear association with K_h while particle size had a negative linear association with both. Bulking agent particle size in the range of 8-12 mm and MC up to 50 % yielded the highest μ_m and K_h. The sum of the readily degradable fraction of organic matter and that requiring hydrolysis, MB_0 and MH_0, respectively, were impacted in an interactive manner by both MC and W/BA ratio. Since the Tremier model is based on OUR, the physical parameters were found to impact the actual rather than the total potential value of MB_0 and MH_0 as the results based on O_2 availability explain. The study reinforces the fact that the physical characteristics of the initial compost mixture are optimized through a holistic approach. The interactive association between MC and W/BA ratio, in particular, was important in influencing the degree of biodegradable matter.

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List of symbols

b is the death coefficient of the microbial mass, h^{-1}

BA is the bulking agent

COD is the chemical oxygen demand, mg O_2 (kg of dry organic matter)$^{-1}$

DM is the dry matter, %

f is the fraction of dead biomass contributing to *MI*, dimensionless

K_b is the concentration of organic matter required to obtain half of μ_m, mmol O_2 (kg dry organic matter)$^{-1}$

K_{mb} is the hydrolysis saturation constant for the ratio MH_t/X_t, mmol O_2 (kg dry organic matter)$^{-1}$

K_h is the hydrolysis rate constant for the fraction *MH* in h^{-1}

MB_0 is the initial mass of readily biodegradable organic matter at time *t*, mmol O_2 (kg dry matter)$^{-1}$

MB_t is the mass of readily biodegradable organic matter at time *t*, mmol O_2 (kg dry matter)$^{-1}$

MI is the fraction of organic matter which is inert in kg (kg of dry matter)$^{-1}$.

MH_0 is the initial fraction of solid or soluble macromolecules at time *t* which first requires hydrolysis to be reduced to the easily biodegradable matter, kg (kg of dry matter)$^{-1}$

MH_t is the fraction of solid or soluble macromolecules at time *t* which first requires hydrolysis to be reduced to the readily biodegradable matter, kg (kg of dry organic matter)$^{-1}$

OM is the organic matter, %

OUR is the oxygen uptake rate, mmol O_2 (kg of dry organic matter - h)$^{-1}$

$R_{O2}(t)$ is the O_2 consumption rate at time *t*, mmol O_2 (kg of dry organic matter - h)$^{-1}$

t is time, h^{-1}

TC is the total carbon, %

TKN is the total Kjeldahl nitrogen, mg N (kg of dry organic matter)$^{-1}$

W/BA ratio is the waste (agro-food sludge) to bulking agent (wood residues recycled from a composting centre) ratio on a dry mass basis, dimensionless

X is the microbial population, mg biomass (kg dry organic matter)$^{-1}$

X_0 is the initial mass of microbial population at time 0, mg biomass (kg dry organic matter)$^{-1}$

X_t is the mass of microbial population at time *t*, mg biomass (kg dry organic matter)$^{-1}$

Y is the coefficient of biomass growth yield, mmol O_2 (mg biomass)$^{-1}$

β_0 is the regression intercept, dimensionless

β_1, β_2, β_3 are the linear coefficients, dimensionless

μ_m is the maximum growth rate of the microbial population, h^{-1}

χ_1 is the MC in %

χ_2 is the W/BA ratio, dimensionless

χ_3 is the BA particle size in mm

Table 1
Description of the experimental sludge and bulking agent

	Sewage sludge	Wood residues				
		8.5 - 12 (mm)	12 - 20 (mm)	20 – 30 (mm)	30 – 40 (mm)	>40 (mm)
Moisture content (%)	86.8	10.0	10.0	10.0	10.0	10.0
OM (% DM)$_{(CV\ \%)}$	83$_{(0.1)}$	91.0$_{(0.1)}$	92.1$_{(0.1)}$	93.9$_{(0.0)}$	93.1$_{(0.1)}$	89.3$_{(0.3)}$
COD (g/kg DM)$_{(CV\ \%)}$	1,331$_{(0.6)}$	1,356$_{(0.1)}$	1 362$_{(0.1)}$	1,370$_{(0.9)}$	1,531$_{(0.7)}$	1,369$_{(0.6)}$
TC (g/kg DM)$_{(CV\ \%)}$	484$_{(0.5)}$	514$_{(0.4)}$	508$_{(0.9)}$	510$_{(0.7)}$	517$_{(3.2)}$	486$_{(2.9)}$
TKN (g/kg DM)$_{(CV\ \%)}$	46.4$_{(1.5)}$	46.1$_{(0.8)}$	37.1$_{(1.0)}$	31.5$_{(0.5)}$	34.3$_{(0.5)}$	23.8$_{(0.9)}$

DM: dry matter basis; CV: coefficient of variation.

Table 2
Experimental compost recipes.

Mixture	Nominal moisture content (%)	Measured moisture content (%)	Bulking agent particle size (mm)	Waste/bulking agent ratio (dry mass basis)	C:N ratio
1	45	41.5	20 – 30	1 / 9.2	14.4
2	60	61.6	12 – 20	1 / 7.9	13.3
3	45	52.5	8 – 12	1 / 6.0	10.4
4	45	49.0	20 – 30	1 / 2.8	13.1
5	70	68.3	20 – 30	1 / 6.0	14.1
6	30	30.3	30 – 40	1 / 7.9	17.7
7	30	35.6	12 – 20	1 / 4.1	16.2
8	60	61.7	12 – 20	1 / 4.1	11.5
9	60	56.0	30 – 40	1 / 4.1	16.5
10	45	51.4	20 – 30	1 / 6.0	14.8
11	45	53.2	> 40	1 / 6.0	21.3
12	30	31.4	12 – 20	1 / 7.9	19.3
13	20	28.5	20 – 30	1 / 6.0	15.3
14	60	61.1	30 – 40	1 / 7.9	17.6
15	45	51.0	20 – 30	1 / 6.0	15.1
16	30	33.5	30 – 40	1 / 4.1	17.6

Table 3
Microbial kinetics and substrate biodegradation components.

Mixture	Maximum growth rate, μ_m (h^{-1})	Hydrolysis rate constant, K_h (h^{-1})	MB_0 (mmol O_2/ kg DM)	MH_0 (mmol O_2/ kg DM)	Total MB_0 + MH_0 (mmol O_2/ kg DM)
1	0.1994	0.1258	959	7953	8912
2	0.1051	0.1014	1264	15342	16606
3	0.2006	0.1172	2085	13169	15254
4	0.1100	0.0873	1763	16300	18063
5	0.1119	0.1165	1429	18156	19585
6	0.0685	0.0849	475	10729	11204
7	0.0961	0.1088	1687	14381	16068
8	0.0978	0.1209	850	14179	15029
9	0.0951	0.0945	928	14710	15638
10	0.1155	0.0975	1186	16753	17939
11	0.1053	0.0813	971	12769	13740
12	0.0845	0.0847	1025	12580	13605
13	0.0805	0.0851	1068	14007	15075
14	0.0960	0.0987	1090	16699	17789
15	0.1159	0.0872	1293	15083	16376
16	0.0851	0.0774	993	14621	15614

Note: MB_0: initial fraction of organic matter being readily degradable; MH_0: initial fraction of organic matter requiring hydrolysis; DM: dry matter.

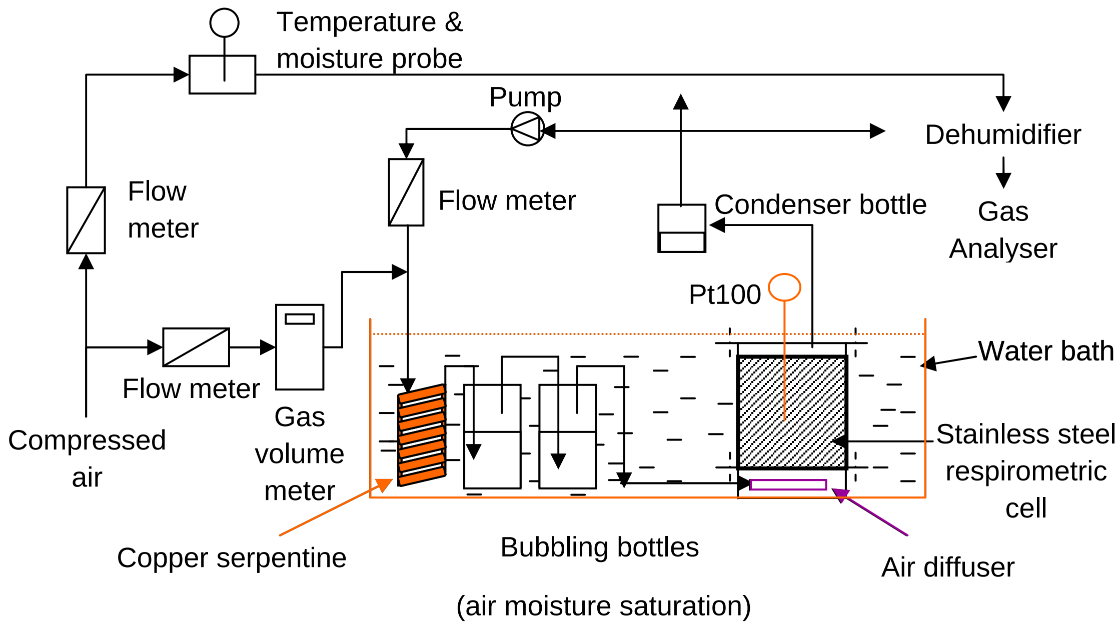

Figure 1. Schematic diagram of respirometry apparatus (Tremier et al., 2005).

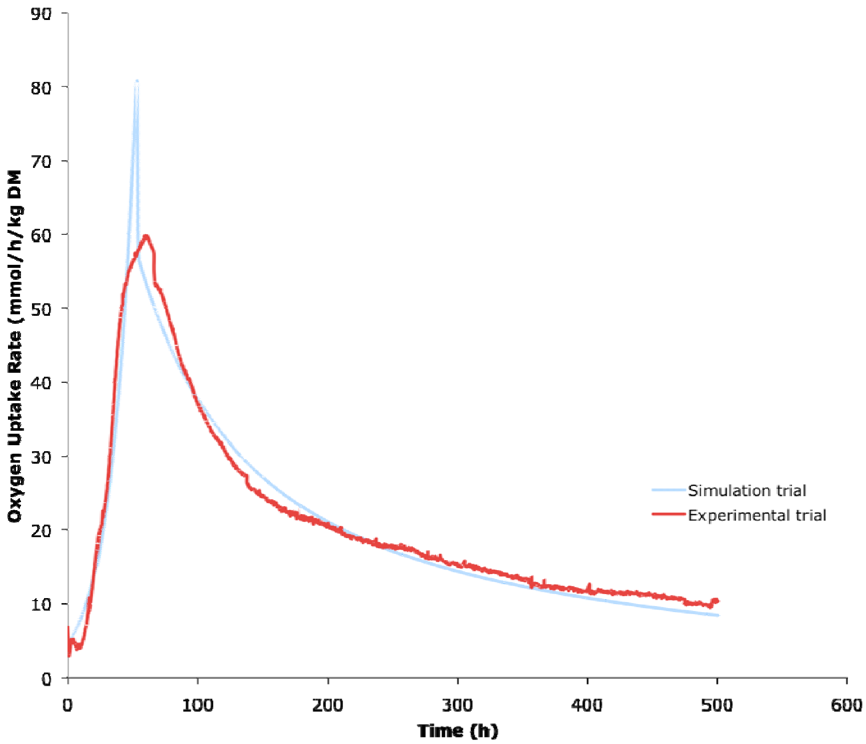

Figure 2. Oxygen uptake rate over time for mixture 4 (moisture content of 49 %; waste to bulking agent ratio of 1/2.8 dry mass; bulking agent particle size of 20-30mm) with the largest variation between experimental and simulation trials.

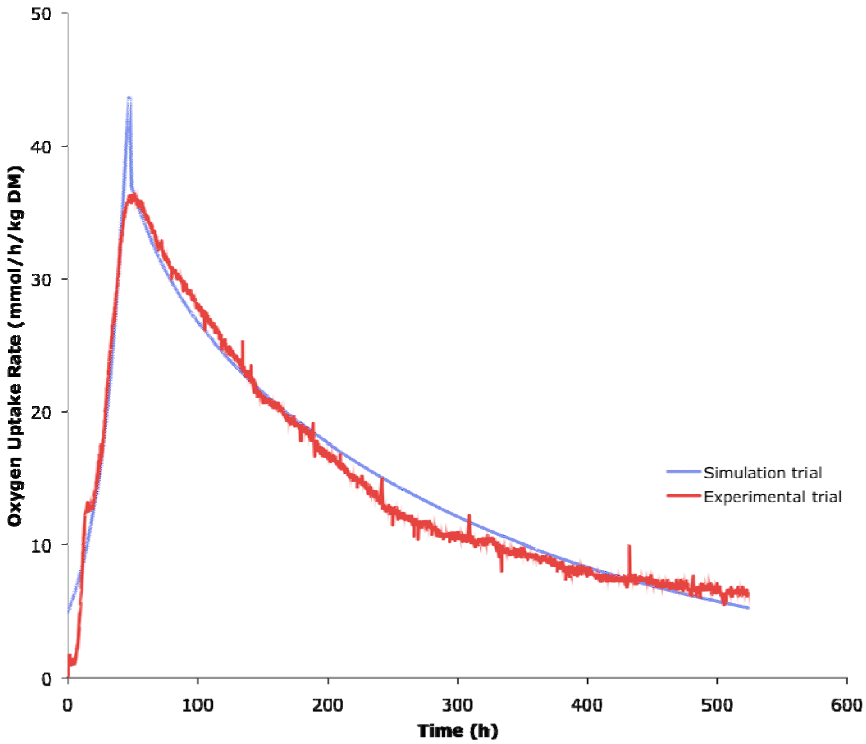

Figure 3. Oxygen uptake rate over time for mixture 9 (moisture content of 56 %; waste to bulking agent ratio of 1/4.1 dry mass; bulking agent particle size of 30-40mm) with the smallest variation between experimental and simulation trials.

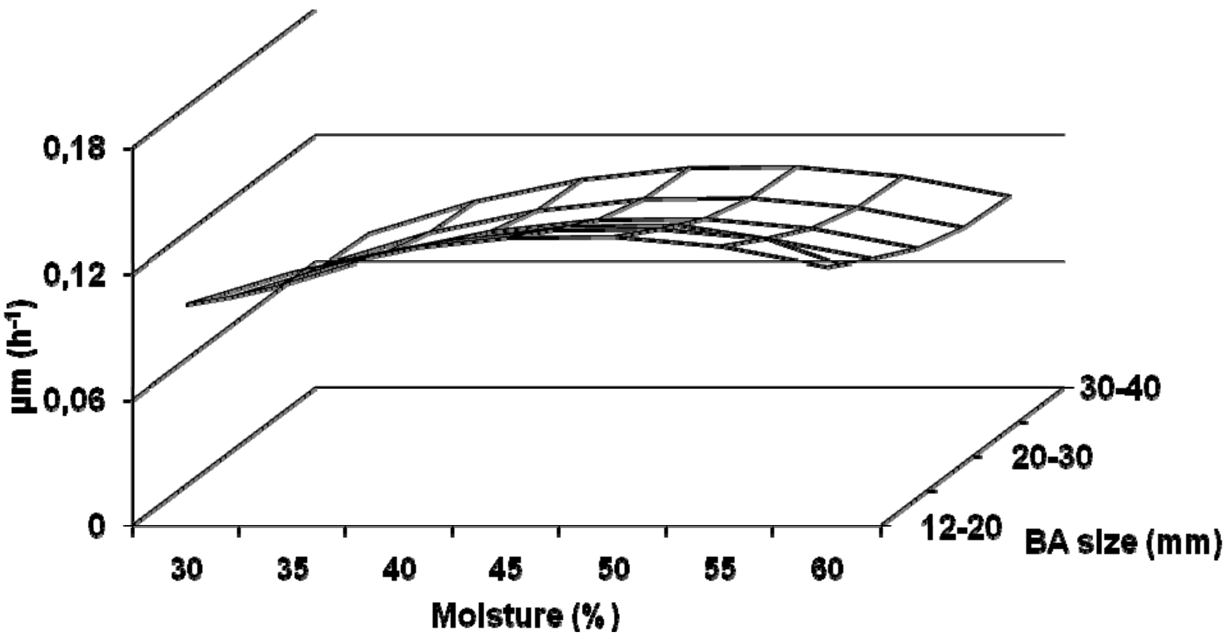

Figure 4. Simulated effect of compost mixture moisture content and bulking agent particle size on the maximum microbial maximum growth, μ_m.

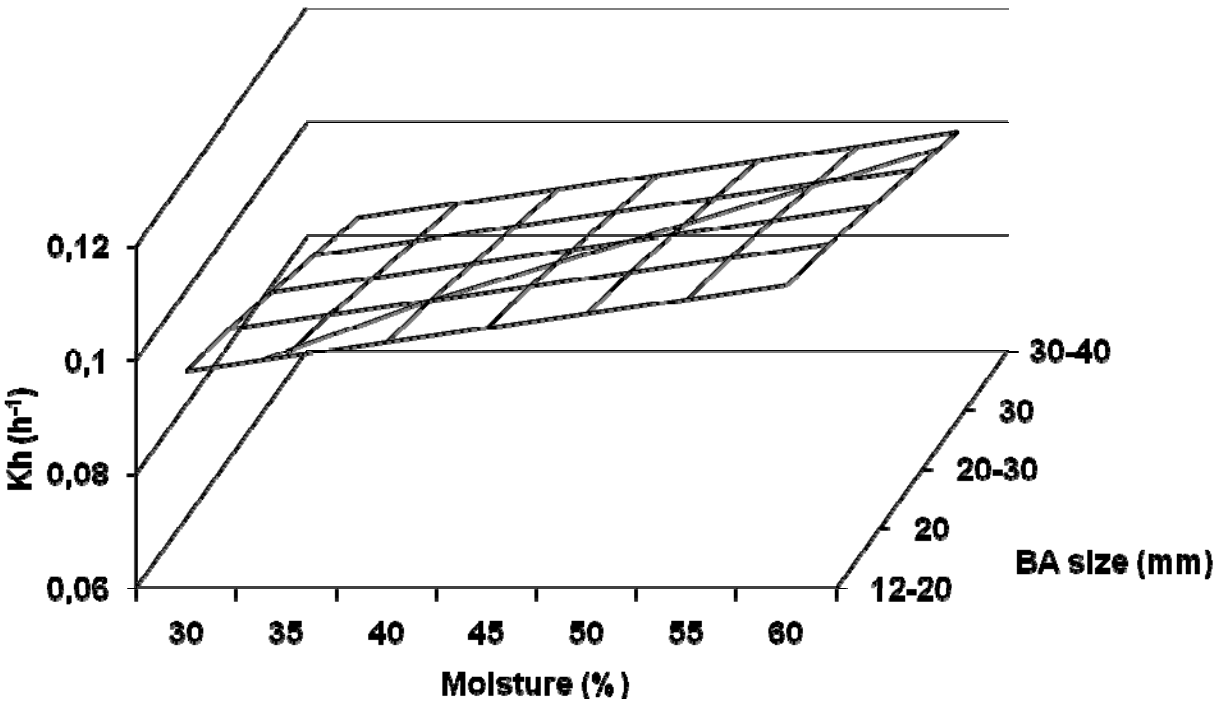

Fig. 5. Simulated effect of compost mixture moisture content and bulking agent particle size on the hydrolysis constant K_h for the organic matter fraction which is not readily degradable, MH_0.

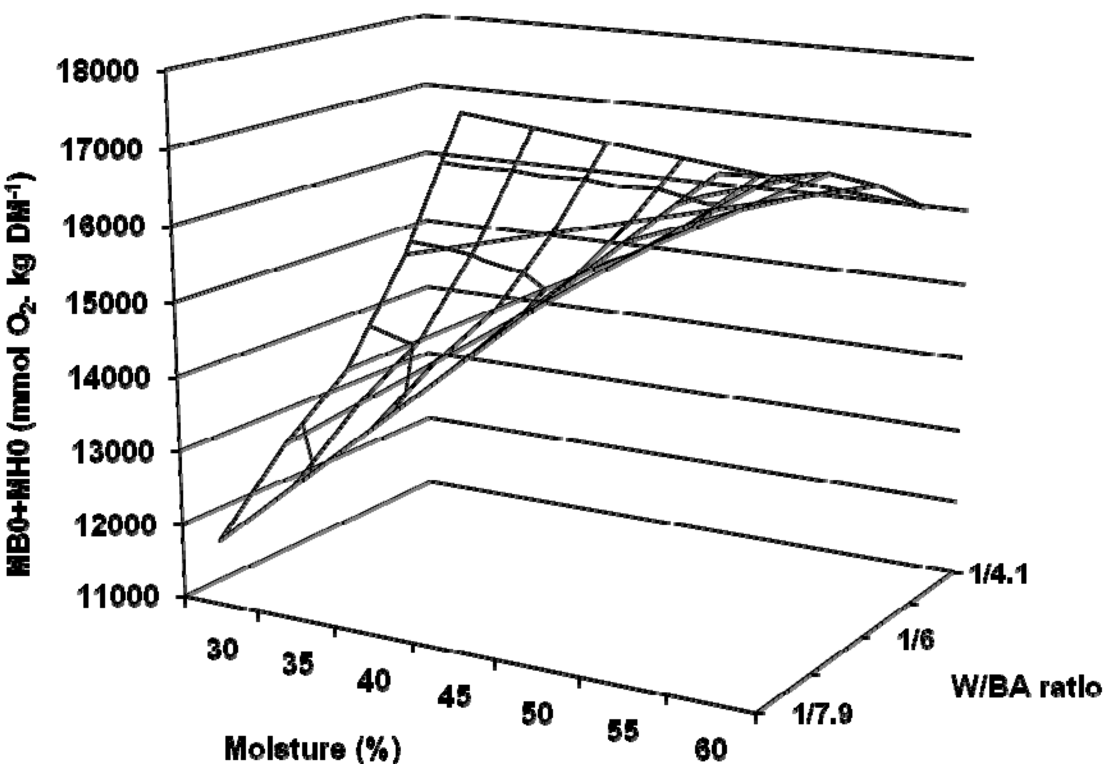

Figure 6. Simulated effect of compost mixture moisture content and waste to bulking agent (W/BA) ratio on the fraction of organic matter which is degraded during composting (MB_0 + MH_0).