

Original Research

Supplementation of Wastewater Process Modelling Tools to Enable the Kinetic Analysis of Sewage Sludge Composting

R. Kovács*, P. Miháلتz, Z. Csikor

Environmental Pilot Laboratory, Department of Chemical and Environmental Process Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3. Budapest, H-1111, Hungary

Received: March 8, 2007

Accepted: June 13, 2007

Abstract

This study demonstrates mathematical description of sewage sludge composting based on identification and separate characterisation of simple process parts. For a description of the microbial processes an ASM3-based mathematical model developed for autothermal thermophilic aerobic sludge digestion is used. The oxygen mass transfer was characterized in a separate way. The $2.964 \cdot 10^{-3} \text{ m}^2 \cdot \text{d}^{-1}$ value of the oxygen diffusion coefficient in the sludge at 55°C indicates the strong oxygen limitation of the microbial degradation. The model extended with the oxygen mass transfer description has been validated using results from composting experiments performed with different specific sludge-air surface areas and with the renewal of the sludge surface.

Keywords mathematical modelling, composting, oxygen diffusivity, thermophilic

Introduction

Composting, the process of producing organic fertilizer through the degradation of organic fractions of sewage sludge, is becoming a focal point of environmental technology. Two main factors contributing to this trend are the increasing amount of sludge produced in municipal wastewater treatment plants and the stricter legislation concerning sludge handling [1]. The growing popularity of the technology makes more obvious the absence of exact, quantitative scientific knowledge of the composting processes.

Using mathematical tools for the description of biological processes is a mature, widely used approach in the field of wastewater treatment technology. However, the processes operated under thermophilic temperature condi-

tions (e. g., the autothermal thermophilic aerobic digestion (ATAD) and composting) were left out of this mathematical modelling development. This does not mean of course that there are no attempts for the mathematical description of composting. One of the main conclusions of Mason's recent review [2] in this field is that an adequate description of the complex composting process can be made only with models that contain empirical relations, which make the model suitable for the description of the actual process but provide poor benefits in general cases.

A good example for this way of modelling is the work of Chang et al. [3] where a modified Gompertz model is used for the prediction of the cumulative CO_2 evolution. One of the strong points of this approach is the low number of model parameters which can be identified separately from experimental results. On the other hand, the parameter values obtained from this model are not universal; as the authors also emphasize, the model calibration is to be performed in every specific case where the model is to be applied.

*Corresponding author; e-mail: robert.kovacs@mail.bme.hu

Sole-Mauri et al. demonstrate an opposite approach in their paper [4]: their highly mechanistic model contains different substrate and biomass fractions in order to account for different biodegradability of the wide range of composting substrates and the substrate specificity of different microbial consortia present in composting biomass. The model's processes are similar to those introduced in Activated Sludge Model No. 1 [5]. The large number of modelled processes results in many parameters. Identification of unique parameter values during model calibration, however, can be problematic, which makes the application of the model difficult.

To overcome these general problems of compost modelling, process elements suitable for separate investigation should be identified. Such an approach allows the separate mathematical description of these process elements and the final mathematical model of the composting can be obtained as the combination of these sub-models.

Nakasaki et al. [6] presented a good example which can be considered as a first attempt at such a separation. In their study they provide a method for the determination of the effective diffusivity of oxygen in dewatered sewage sludge. According to their method, the microbial respiration disturbing the measurement is eliminated by treatment of the sewage sludge with gamma-irradiation. This does not modify the structure of the dewatered sludge, therefore it makes possible the separate study of oxygen diffusion. However, the reported diffusivity measurements were performed at 27°C using sewage sludge with very high lime and ferric chloride content. This and the oversimplified evaluation method resulted in oxygen diffusivity coefficients that have very limited use at thermophilic temperatures.

The microbial degradation rate during composting can be limited by oxygen diffusion in the dewatered sludge. Results of Lasaridi and Stentiford [7] demonstrate this limitation using a very simple yet effective approach: they performed respiration measurements in water suspension of composted sludge samples in order to characterize compost stability. It has been found that the respiration rate can be an order of magnitude larger in the suspended sludge than in the dewatered state.

This method of suspending the composting sludge in water gives the opportunity to eliminate the diffusion limitation from the composting process and study the kinetic relations of the microbial degradation. The autothermal thermophilic aerobic sludge digestion can be considered as such a suspension of composting sludge so the question arises whether microbial kinetic results obtained with the ATAD process can be used for the description of composting.

The terminology of calling the ATAD process 'liquid composting' [8] suggests the microbial identity of the processes. This can be confirmed by microbial community analyses concerning both ATAD and composting. Nakasaki et al. [9] demonstrated that thermophilic bacteria play a dominant role during sewage sludge composting. The same is true in the case of organic decomposition in the

liquid phase. The activity of thermophilic actinomyceta and fungi is much smaller, or in the case of fungi it can be neglected in the intensive phase of the degradation. Microbial community analyses of composting of dried table scraps, shredded newspaper, or household waste showed that thermophilic bacteria belonging to *Bacillus* spp. are mostly active in decomposition [10, 11]. The same *Bacillus* species were found in the thermophilic aerobic treatment of wastewater [12]. These results suggest that experience obtained with microbial processes in ATAD can be used for the kinetic characterization of sewage sludge composting.

In addition to oxygen diffusion limitation in dewatered sludge there are, of course, other influential factors in full-scale composting applications. The most important ones, such as air-filled porosity, air permeability of the pile and moisture content, are the focus of the research of Richard et al. [13, 14]. They present an extensive framework for the description of interrelation of air-filled porosity, permeability and mechanical strength of solid substrates in solid-state fermentations [13]. This makes possible the quantitative characterization of the effects of e. g. bulking agent particle size and pile compaction, which is very important in composting. This approach is extended in [14], where the connections between moisture content of composting sludge and other relevant pile properties (porosity, bulk density of wet and dry matters) are summarized in a systematic framework.

This work demonstrates the application of the approach of characterizing the composting process as a sum of simple and easily observable and identifiable subprocesses as discussed above. As a first step, in this paper we focus on modelling lab-scale sludge composting. This means that the limitations that are introduced by large pile dimensions (compaction, reduced permeability and porosity) can be neglected. According to this only the characterisation of the oxygen diffusion and the microbial degradation is included. The modelling work can be detailed as follows:

1. The mathematical model presented by Kovács et al. [15] was used for the microbial characterization of the composting process. This is an extended and calibrated version of the Activated Sludge Model No. 3 [16].
2. The investigation of oxygen diffusion in dewatered sludge required the measurement of the diffusion coefficient at thermophilic temperatures using conventional dewatered mixed sludge.
3. The validation of the resulting complex model was made using experiments that allowed direct study of oxygen limitation. Composting tests performed with various air-sludge specific surface areas made possible the characterisation.
4. Another model validation method comes from the fact that owing to the oxygen diffusion limitation the microbial degradation takes place only along the air-sludge surface area. This results in a reduced microbial activity in a few hours, this time owing to the depletion of the substrate along the surface. The microorganisms

can be reactivated by transporting the substrate from the bulk to the surface, i. e. by the homogenization of the sludge. Model verification based on data from such experiments is also presented.

Experimental Procedures

Sewage Sludge

Dewatered sewage sludge obtained from the conventional activated sludge wastewater treatment plant of Batorbágy, Hungary, was used in our experiments. It was stored at 4°C in a dewatered state until further use.

Diffusivity Measurements

The experimental setup of the oxygen diffusivity measurements was based on the method reported by Nakasaki et al. [6]. However, some significant changes were applied in order to enhance the reliability of the results. The air compartment of the measuring reactor (Fig. 1) was filled with pure oxygen instead of air to increase the driving force of the diffusion. A WTW TriOxMatic EO 200 oxygen electrode was applied for oxygen concentration monitoring on the oxygen side and a WTW EO 96 electrode on the nitrogen side. The microorganisms inherent to the sewage sludge were inactivated using beta-irradiation. The dose of the irradiation was 42-44 kGy which is safe enough to inactivate all microbes. The experiments were thermostated at 55°C.

The evaluation of the measurement results is simple due to the inactivation of the microbes. The diffusivity can be expressed from Fick's First Law (Eq. 1).

$$J = -D_{O_2} \frac{\partial S_{O_2}}{\partial x} \quad (1)$$

The change of the oxygen concentration in time can be expressed using the oxygen mass balance in the reactor (Eq. 2) in the form of Eq. 3, where it is exploited

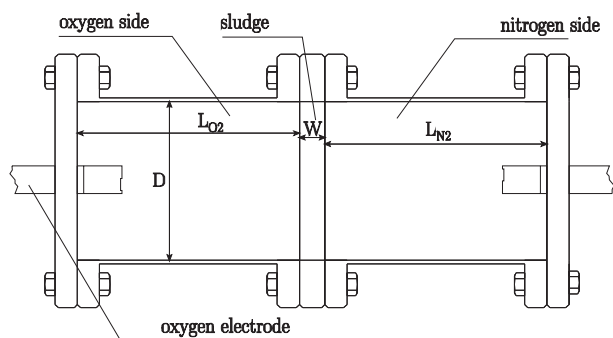


Fig. 1. Measurement system for the determination of the effective diffusivity in dewatered sludge cake. The dimensions of the reactor are as follows: $L_{O_2}=L_{N_2}=0.1$ m, $W=0.006$ m, $D=0.054$ m.

that the volumes of nitrogen and oxygen compartments are equal.

$$G_{O_2,10}V_{O_2} = G_{O_2,1}(t)V_{O_2} + G_{O_2,2}(t)V_{N_2} \quad (2)$$

where $G_{O_2,1}$ and $G_{O_2,2}$ is the oxygen concentration in the oxygen and nitrogen space respectively.

$$\frac{dS_{O_2,1}}{dt} = \frac{D_{O_2}A}{V_{O_2}H_{O_2}M_{O_2}P} \frac{RT}{W} \frac{S_{O_2,10} - 2S_{O_2,1}}{W} \quad (3)$$

where H_{O_2} is the constant of Henry's Law defined in Eq. 4. For the sake of simplicity it is assumed that H_{O_2} has the same value in the case of sludge as in pure water. According to previous experience with thermophilic sludge digestion the simplification does not introduce significant error in the calculation.

$$H_{O_2} = \frac{G_{O_2}}{S_{O_2}} \quad (4)$$

Eq. 3 has the solution according to Eq. 5:

$$S_{O_2,1} = \frac{S_{O_2,10}}{2} + \frac{S_{O_2,10}}{2} e^{\left(-\frac{2tAD_{O_2}}{V_{O_2}WH_{O_2}M_{O_2}P} \frac{RT}{W}\right)} \quad (5)$$

Oxygen diffusivity can be determined by fitting Eq. 5 to the measured oxygen concentration data. As can be seen, this evaluation method is different from that of Nakasaki et al. [6]. Their simple approach resulted in a diffusion constant based on gas phase oxygen concentrations different from the standard diffusion coefficient of oxygen in liquid as determined here.

Experiments for the Determination of the Effect of Specific Sludge-Air Interface Area

Setting of exact values of specific surface of the sludge was made by spreading the sludge on square glass plates with 7×7 cm dimensions. The glass plates covered with sludge were placed into closed vessels with a volume of 1.5 L and were thermostated at 55°C. The ammonia and carbon-dioxide produced during the degradation were absorbed in 1M H_2SO_4 and 1M NaOH solutions, respectively. The pressure change due to oxygen consumption was measured with WTW Oxitop pressure sensors. The oxygen uptake rate was calculated from the pressure change using Eq. 6.

$$OUR = \frac{dm_{O_2}}{dt} \frac{1}{m_{VS}} = \frac{\frac{dp}{dt} V_r M_{O_2}}{RT m_{VS}} \quad (6)$$

All experiments were performed using 30 g of sludge placed into one reactor. Applying 1, 2 and 4 glass plates per reactor resulted in 163.3, 326.7 and 653.6 m²·m⁻³ specific surface areas, respectively.

Experiments for Investigating the Effect of Renewal of Sludge-Air Interface (“Mixing”)

Execution of fast surface renewal was an important aspect during these experiments. Consequently, a special reactor was built where the surface renewal could be made inside the composting reactor without disturbing the system. The schematic diagram of the reactor can be seen in Fig. 2. The surface renewal at the specified time was made by a moving perforated piston. Holes in the piston with a diameter of 2 mm allowed the extrusion of cylindrical sludge strings with known diameters and thus known specific surfaces.

During the composting experiments the sludge was aerated with an air flow of 20 l·h⁻¹. The carbon dioxide concentration in the exhaust air was used for monitoring microbial activity. A special instrument with a measuring principle based on membrane separation and catalytic reduction of CO₂ to methane from the gas phase [17] was

used to monitor carbon dioxide with high precision in the reactor off-gas. Measurement of carbon dioxide was chosen for monitoring the respiration activity in this case because it allows very sensitive respiration measurement. Exploiting this high sensitivity of the instrumentation, a larger air flow became applicable, which was needed because of the assumption of a homogeneous gas phase in the composting reactor.

The oxygen uptake rate from the exhaust carbon dioxide concentration can be calculated according to Eq. 7.

$$OUR = RQ \frac{Q_{air} G_{CO_2}}{m_{VS}} \quad (7)$$

Although the value of RQ depends on respiration intensity [18], the intensive degradation is limited to a very narrow zone of the composting sludge as it is presented below. This means that almost all of the sludge cross section can be considered to be in an inactive/endogenous stage. This justifies an RQ value of 0.9 mol CO₂·mol O₂⁻¹ which is characteristic to moderate respiration rates according to [18].

Modelling Approach

Mathematical models were built in GNU Octave [19]. With the modelling of oxygen diffusion the model was extended with the change of oxygen concentration in space. This extension transforms the model into a partial differential equation system. Since solving such a system usually requires special methods and conditions, the following simplifications were used: The composting sludge was divided into layers parallel with the air-sludge interface. The layers were supposed to be homogeneous (i. e., no concentration gradients inside). Such a division is illustrated in Fig. 3.

It was assumed that the outmost layer is in equilibrium with the air. Using the notation of Fig. 3 this means that the oxygen concentration in that layer can be calculated according to Eq. 8.

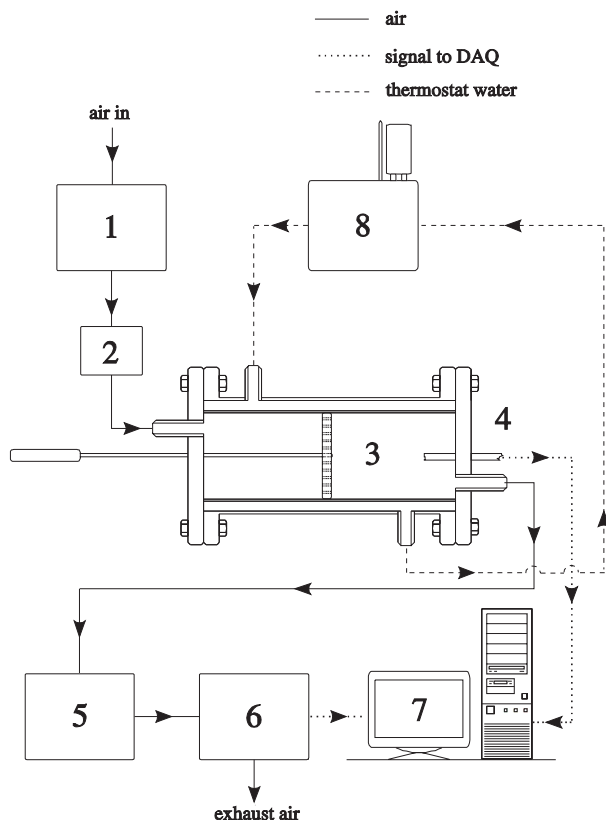


Fig. 2. Experimental setup of the surface renewal tests. 1. air humidifier unit; 2. air flow meter unit; 3. thermostated reactor with a moving perforated piston; 4. temperature sensor; 5. air dryer unit; 6. CO₂ sensor; 7. data acquisition and control system; 8. thermostat bath.

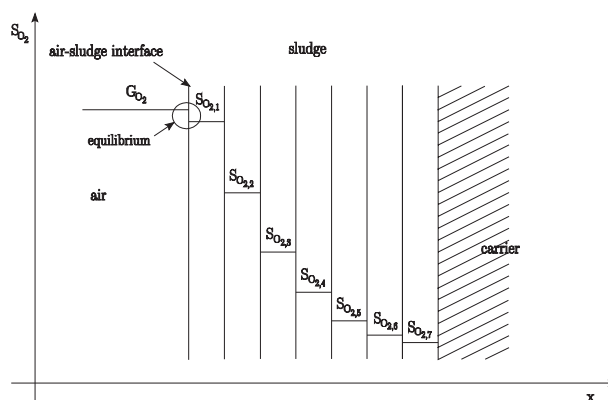


Fig. 3. Division of dewatered sludge cake into layers.

$$S_{O_2,1} = \frac{G_{O_2}}{H_{O_2}} \quad (8)$$

For the inner layers Fick's First Law has been used, where the spatial derivative can be approximated using forward and backward differences in terms of the concentrations of the neighbouring layers. Using this approximation, the oxygen mass balance of the n -th layer is expressed in Eq. 9.

$$\begin{aligned} \frac{dS_{O_2,n}}{dt} = & -\frac{D_{O_2} A}{V_l} \frac{S_{O_2,n} - S_{O_2,n-1}}{w_l} + \\ & + \frac{D_{O_2} A}{V_l} \frac{S_{O_2,n+1} - S_{O_2,n}}{w_l} - r \end{aligned} \quad (9)$$

where r is the oxygen uptake rate of the microorganisms in the respective layer, according to the extended ASM3 model presented by Kovács et al. [15]. The model does not contain the turnover of the substrate and biomass between the layers i. e., only oxygen diffusion is considered.

Results

Results of the Diffusivity Measurements

The results of a typical diffusivity measurement performed at 55°C are demonstrated in Fig.4. The value of effective oxygen diffusivity resulted in $2.964 \cdot 10^{-3} \text{ m}^2 \text{ d}^{-1}$.

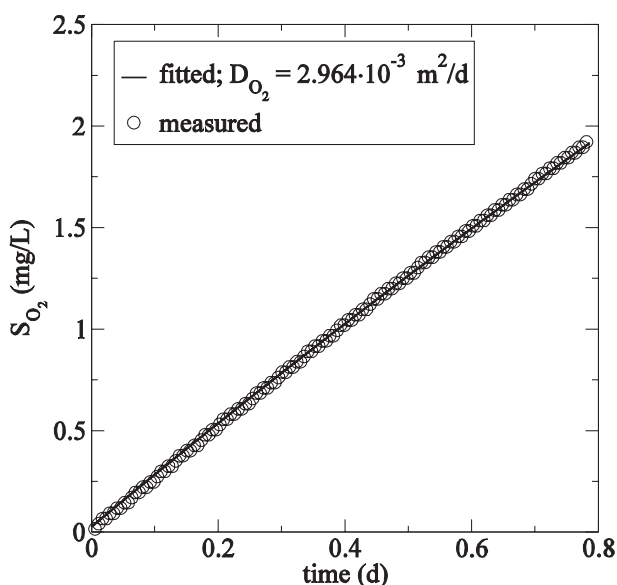


Fig. 4. Results of a diffusivity measurement at 55°C – oxygen concentration data measured in the reactor space initially filled with nitrogen.

Effect of the Specific Air-Sludge Surface on the Degradation Rate

The effect of the specific surface on the oxygen uptake rate is demonstrated in Fig. 5. As can be seen from the figure, the larger specific surface values allow a more intensive oxygen uptake rate, i. e. faster degradation. The maximal respiration rates are 6, 13 and 20 $\text{mg} \cdot \text{gVS}^{-1} \cdot \text{h}^{-1}$ at 163.3, 326.7 and 653.6 $\text{m}^2 \cdot \text{m}^{-3}$, respectively. The reason for the faster drop of respiration rates at more intensive degradation rates is that at faster oxygen consumption the range of limiting oxygen concentration in the closed vessel is reached earlier (Fig. 6). The experimental respira-

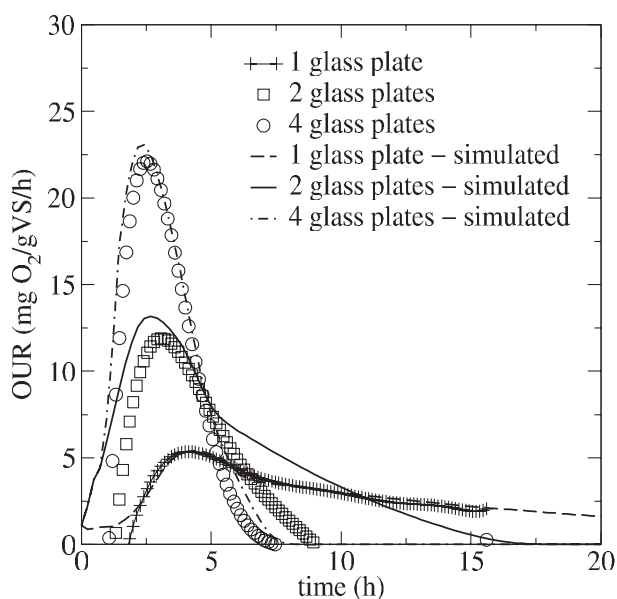


Fig. 5. Effect of the specific air-sludge surface on the degradation rate.

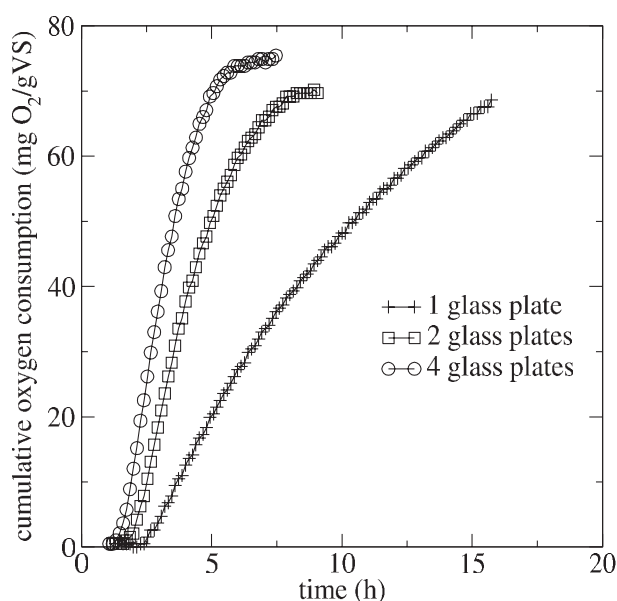


Fig. 6. Cumulative oxygen consumption with different specific air-sludge surface.

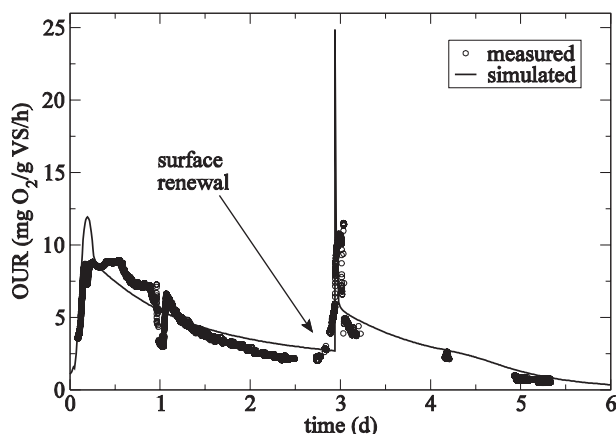


Fig. 7. Effect of surface renewal on the respiration rate during composting.

tion rates can be reproduced by the extended model as seen in Fig. 5.

Effect of the Surface Renewal on Degradation

As seen in Fig. 7, the surface renewal at 3 d is followed immediately by an intensive respiration (from about 2 mg O₂·gVS⁻¹·h⁻¹ to values above 10 mg O₂·gVS⁻¹·h⁻¹). The experiment can be described by the extended mathematical model (continuous line) introduced above.

Discussion of Results

Oxygen Diffusivity

The measured diffusivities in our experiments are about an order of magnitude larger than oxygen diffusion coefficients reported in water at 55°C ($4.22 \cdot 10^{-4} \text{ m}^2 \text{ d}^{-1}$ as extrapolated from data published in Landolt and Börnstein [20]). Considering the high viscosity of dewatered sludge, a much smaller value is expected; however, the hypothesis of Nakasaki et al. [6] considering the structure of the dewatered sludge provides an explanation to this discrepancy. According to that the sludge in dewatered state consists of two parts: solid and void. The void part is completely filled with water right after dewatering. When the sludge loses water the void spaces become partially filled with air, which results in considerable enlargement of the effective diffusivity. Water loss can occur due to drying or it can occur spontaneously during storage as is the case in our situation.

Effects of Oxygen Transfer Limitation

The measured oxygen diffusion coefficient values of Nakasaki et al. [6] are near to our results. However, based

on this value they conclude that oxygen diffusion does not limit microbial oxygen uptake rate. One of their main assumptions is that the oxygen uptake rate measured at the sludge-air interface is applicable through the entire depth of the sludge cake. However, the mathematical model used here for modelling the specific surface and surface renewal tests reveals that this is not the case.

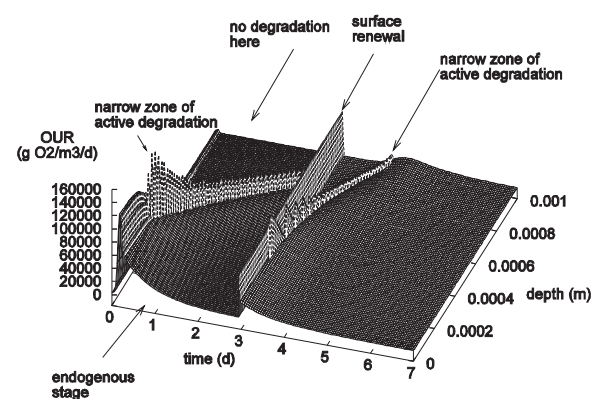
Fig. 8 contains the detailed simulation results of the surface renewal test presented in Fig. 7. As can be seen from Fig. 8a the respiration can be observed in a very narrow zone and this zone is slowly moving with time further from the air-sludge boundary. Behind this narrow active zone there is no oxygen (dissolved oxygen values in sludge are presented in Fig. 8b) and thus no respiration, while in the outer layers organic substrate availability limits degradation (for the readily biodegradable substrate concentrations see Fig. 8d).

Despite the very intensive respiration in the narrow active zone, the respiration that can be measured has moderate values (Fig. 7) since the largest fraction of the sludge is inactive from the point of view of the respiration. It can be seen that the reason for the intensive respiration right after the renewal is that owing to the mixing effect of the surface renewal the concentration gradients in the sludge become negligible. This means that after the renewal there is degradable substrate right at the air-sludge boundary again, which enables rapid degradation. The obvious conclusion is that the larger the specific surface the faster the microbial metabolism. This fact can explain the effects of specific surface and the surface renewal tests.

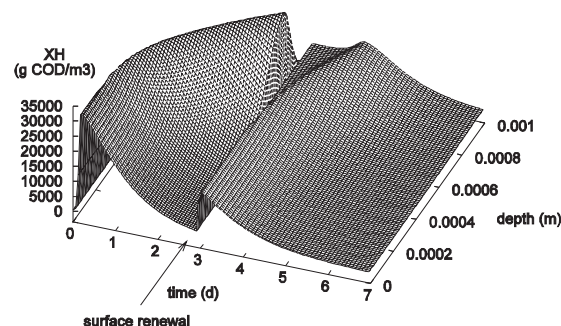
Conclusions of the Results Concerning the Most Frequent Solution for Sewage Sludge Composting: Using Wood Chips as Amendment

As demonstrated above, the mathematical model allows the characterization of the oxygen and substrate profiles within composting sludge. This can be particularly useful for the identification of the rate limiting steps of the composting process. For illustrating the model's capabilities, theoretical calculations were made for a conventional wood chips-sludge compost mix, where the steady-state oxygen profiles were calculated. For the determination of the sludge coating width around the bulking agent particles it was assumed that the sludge coats the particles uniformly. In sludge composting practice a 2:1 bulking agent:sludge volumetric ratio is usually applied. Considering this volume ratio, thickness of sludge coating in the case of different bulking agent particle geometries can be found in Table 1.

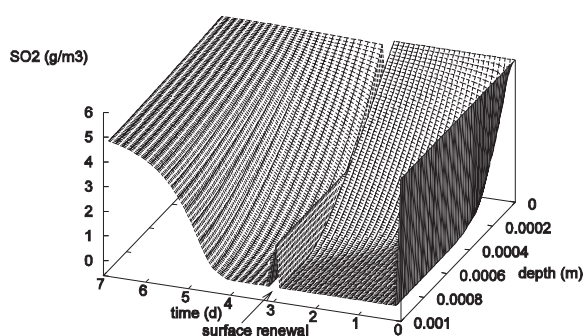
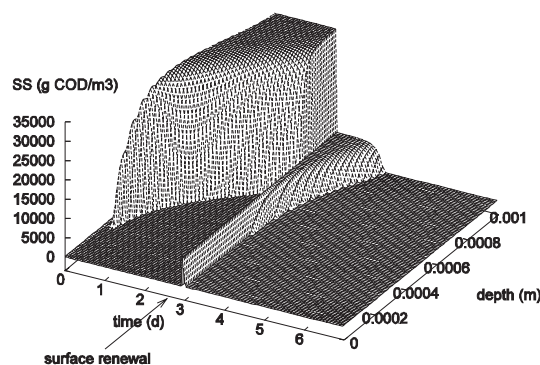
The calculated steady-state oxygen profiles at different effective oxygen uptake rates (i. e., oxygen uptake rates measured outside the sludge cake) can be found in Fig. 9. The subfigure is constructed from the oxygen profile data and contains the oxygen penetration depth vs. the effective oxygen uptake rate. The distance of 0.17 g/m³ oxygen concentration from the air-sludge interface was



a) oxygen uptake rate (OUR)



c) active thermophilic biomass (XH)

b) dissolved oxygen (SO₂)

d) readily biodegradable substrate (SS)

Fig. 8. Simulation results of a surface renewal experiment. The subfigures show the state and composite variables of the model. The sludge-air interface is at depth = 0 m.

Table 1. Thickness of sludge coating on bulking agent particles with different bulking agent particle dimensions at bulking agent:sludge volume ratio of 2:1 which is usual in practice when using wood chips as bulking agent.

Bulking agent particles	Specific surface (m ² ·m ⁻³)	Thickness of sludge coating on particles (m)
cubes with 1 cm long edges	600	0.00083
brick shaped of 2×2×1 cm	400	0.0013
spheres with a diameter of 1 cm	600	0.00083
wood chips (from Phillips et al. [16])	160	0.0031

used as the oxygen penetration depth because the oxygen half saturation constant denoting limiting oxygen concentrations is included in the mathematical model of Kovács et al. [15] with this value.

As can be seen from the profiles and the subfigure, only the outer 0.5-1 mm of the sludge can be considered active from the aspect of biodegradation at the

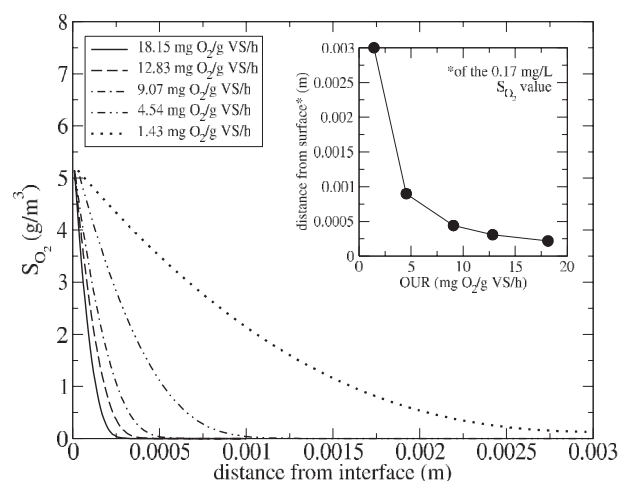


Fig. 9. Dependence of oxygen penetration on microbial respiration.

usual maximal respiration rates of 5-10 mg O₂/g VS/h. Since in the usual case of composting using wood chips the sludge coating around the wood particles is about 3 mm wide (see Table 1), two thirds of the sludge can be considered as inactive mass. The evident solution for increasing the overall degradation rate is the reduction

of the sludge coating width, which can be accomplished either by an increase of the bulking agent specific surface or by the increase of the bulking agent/sludge ratio during composting. While the second option raises serious problems concerning the composting reactor volume and the autothermal properties of the process, the first can provide a good solution. As can be seen in Table 1, in the case of brick-shaped particles with dimensions of $2 \times 2 \times 1$ cm the sludge coating width reduces to about 1 mm and this particle size is not likely to reduce the free air space in the compost pile so that it causes problems with aeration. The same tendencies (i. e. smaller bulking agent particles) are found to be favorable in the work of Gea et al. [22]. Although they investigated the effect of bulking agent particle size on heat retention and disinfection, the strong correlation between aerobic respiration and heat generation [23] makes it obvious that the experimental results of Gea et al. confirm the model results presented here.

Conclusions

A mathematical description of sewage sludge composting based on identification and separate characterization of simple process parts was demonstrated in this study. Based on the microbial identity of the autothermal thermophilic aerobic sludge digestion and the sludge composting, a mathematical model developed for autothermal thermophilic digestion was used for the description of microbial processes. The oxygen mass transfer was characterized using oxygen diffusivity measurements. The model extended with the oxygen mass transfer description has been validated using results from sewage sludge composting experiments. Although the model cannot describe the effects of all environmental conditions in its current state (e. g., it was calibrated and validated only with experimental results obtained at 55°C), its capabilities for the identification of rate limiting steps in the composting process can be of practical use in the field of intensification of the composting process. An example of intensification possibilities was demonstrated concerning sludge composting with wood chips as bulking agent. It has been shown that reducing the bulking agent particle dimensions can result in faster organic matter degradation.

Acknowledgements

The authors would like to thank Mária Bódy for her valuable help in the beta-irradiation of the sewage sludge used for diffusivity measurements.

Nomenclature

A – area of the air-sludge interface (m^2)

D – diameter of the reactor used for diffusivity measurements (m)

D_{O_2} – effective diffusivity of oxygen ($\text{m}^2 \cdot \text{d}^{-1}$)

G_{O_2} – oxygen concentration in air ($\text{m}^3 \cdot \text{m}^{-3}$)

H_{O_2} – constant in Henry's Law for oxygen ($\text{m}^3 \cdot \text{g}^{-1}$)

L_{O_2} – oxygen mass flux ($\text{g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$)

L_{O_2} / L_{N_2} – length of oxygen/nitrogen space in diffusivity measurements (m)

M_{O_2} – molar weight of oxygen gas ($\text{g} \cdot \text{mol}^{-1}$)

m_{O_2} – oxygen mass (g)

m_{VS} – mass of volatile solids (g)

p – atmospheric pressure (Pa)

Q – air flow ($\text{m}^3 \cdot \text{d}^{-1}$)

R – universal gas constant ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$)

RQ – respiratory quotient $\text{mol CO}_2 / \text{mol O}_2$

S_{O_2} – dissolved oxygen concentration in sludge ($\text{g} \cdot \text{m}^{-3}$)

t – time (d)

T – absolute temperature (K)

V_l – volume of one sludge layer (m^3)

V_r – reactor volume in specific surface experiments (m^3)

V_{O_2} / V_{N_2} – volume of oxygen/nitrogen space of diffusivity measuring reactor (m^3)

W – width of sludge cake in diffusivity experiments (m)

w_l – width of one sludge layer (m)

References

1. COUNCIL OF THE EUROPEAN COMMUNITY. Council Directive 1999/31/EC of 26 April 1999 on the Landfill of Waste. OJ. L. **182**, 1, **1999**.
2. MASON I. G. Mathematical Modelling of the Composting Process: A Review. *Waste Manage.* **26**, 3, **2006**.
3. CHANG J. I., TSAI J. J., WU K. H. Mathematical Model for Carbon Dioxide Evolution from the Thermophilic Composting of Synthetic Food Wastes Made of Dog Food. *Waste Manage.* **25**, 1037, **2005**.
4. SOLE-MAURI F., ILLA J., MAGRÍ A., PRENAFETA-BOLDÚ F. X., FLOTATS X. An Integrated Biochemical and Physical Model for the Composting Process. *Biores. Technol.* [in press], **2006**.
5. HENZE M., GRADY C. P. L., GUJER W., MARAIS G. v. R., MATSUO T. Activated Sludge Model No. 1. Technical Report, IAWPRC Scientific and Technical Reports, London, UK, **1987**.
6. NAKASAKI K., NAKATO Y., AKIYAMA T., SHODA M., KUBOTA H. Oxygen Diffusion and Microbial Activity in the Composting of Dehydrated Sewage Sludge Cakes. *J. Ferment. Technol.* **65**, (1), 43, **1987**.
7. LASARIDI, K. E., STENTIFORD, E. I. A Simple Respirometric Technique for Assessing Compost Stability. *Water Res.* **32**(12), 3717, **1998**.
8. KELLY H. G., DONALD S. M., KOCH F. A., WETTER R. D., MELCHER H. Liquid Composting of Municipal Sludge for Agricultural Use in Small Communities: Canadian Application. IAWPRC Proceedings, Sludge Management Conference, Los Angeles, CA, Jan. **1990**.

9. NAKASAKI K., SASAKI M., SHODA M., KUBOTA H. Change in Microbial Numbers During Thermophilic Composting of Sewage Sludge with Reference to CO₂ Evolution Rate. *Appl. Environ. Microbiol.* **49**, (1), 37, **1985**.
10. STROM P. F. Identification of Thermophilic Bacteria in Solid Waste Composting. *Appl. Environ. Microbiol.* **50**, (4), 906, **1985**.
11. GHAZIFARDA., KASRA-KERMANS SHAHI R., FAR E. Z. Identification of Thermophilic and Mesophilic Bacteria and Fungi in Esfahan (Iran) Municipal Solid Waste Compost. *Waste Manage. Res.* **19**, 257, **2001**.
12. KURISU F., SATOH H., MINO T., MATSUO T. Microbial Community Analysis of Thermophilic Contact Oxidation Process by Using Ribosomal RNA Approaches and the Quinone Profile Method. *Water Res.* **36**, 429, **2002**.
13. RICHARD T. L., VEEKEN A. H. M., WILDE V., HAMELERS H. V. M. Air-Filled Porosity and Permeability Relationships during Solid-State Fermentation. *Biotechnol. Prog.* **20**, 1372, **2004**.
14. RICHARD T. L., HAMELERS H. V. L., VEEKEN A., SILVA T. Moisture Relationships in Composting Process. *Compost Sci. Util.* **10**, 286, **2002**.
15. KOVÁCS R., CSIKOR ZS., MIHÁLTZ P. Application of Activated Sludge Model No. 3 for the Modelling of Organic Matter Biodegradation at Thermophilic Temperatures. *Water Environ. Res.* [in press], **2007**.
16. GUJER W., HENZE, M., MINO T., LOOSDRECHT M. Activated Sludge Model No. 3. *Water Sci. Technol.* **39**, (1), 183, **1999**.
17. NAGYGYÖRÝ SZ., WITTMAN M., PINTÉR S., VISEGRÁDY A., DANCÓS A., THUY N. B., NOSZTICZIUS Z., HEGEDŰS L., FÖRSTERLING H. D. Alternative Reaction Channels and Carbene Intermediates in the Ce⁴⁺-Malonic Acid and Ce⁴⁺-Bromomalonic Acid Reactions. 1. CO₂ Measurements. *J. Phys. Chem. A.* **103**, (25), 4885, **1999**.
18. KOVÁCS R., MIHÁLTZ P., CSIKOR ZS. Connection Between Oxygen Uptake Rate and Carbon Dioxide Evolution Rate in Aerobic Thermophilic Sludge Digestion. *Periodica Polytech., Chem. Eng.* [in press], **2007**.
19. EATON J. W. GNU Octave Manual. Network Theory Limited, Bristol, UK, **2002**.
20. LANDOLT H., BÖRNSTEIN R. Numerical Data and Functional Relationships in Science and Technology. Springer Verlag, Berlin, **1993**.
21. PHILLIPS V. R., SCOTFORD I. M., WHITE R. P., HARTSHORN R. L. Minimum-Cost Biofilters for Reducing Odours and Other Aerial Emissions From Livestock Buildings: Part 1, Basic Airflow Aspects. *J. Agric. Engng. Res.* **62**, 203, **1995**.
22. GEA T., BARRENA R., ARTOLA A., SÁNCHEZ A. Optimal Bulking Agent Particle Size and Usage for Heat Retention and Disinfection in Domestic Wastewater Sludge Composting. *Waste Manage.* [in press], doi:10.1016/j.wasman.2006.07.005, **2006**.
23. AULENTA F., BASSANI C., LIGTHART J., MAJONE M., TILCHE A. Calorimetry: A Tool for Assessing Microbial Activity Under Aerobic and Anoxic Conditions. *Water Res.* **36**, 1297, **2002**.