MODELING COMPOSTING KINETICS: A REVIEW OF ENVIRONMENTAL APPROACHES

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Abstract: Composting kinetics modeling is necessary to design and operate composting facilities that comply with strict market demands and tight environmental legislation.Current composting kinetics modeling can be characterized as inductive, i.e. the data are the starting point of the modeling process and determine the type of model used. It is argued that the inductive empirical approach has been developed to its limit of practicality. Further progress is not expected because of limits in measurement techniques and the resources needed to perform all experiments needed. Contrary to the inductive, the deductive modeling approach uses the existing theory as its starting point for model development. Deductive models of realistic situations contain many basic parameters representing the theoretical basis. These basic parameters however tend to be non-identifiable, limiting practical application. To overcome this problem, it is proposed that the basic parameters in the deductive model must be combined to a smaller number of so-called combined parameter that are identifiable. In this way a model is developed that can incorporate both the theoretical knowledge introduced via the basic parameter and the information of data as represented by the identifiable combined parameters.

Key words: composting kinetics, deductive model

1. INTRODUCTION

Proper design and operation of the composting reactor is necessary to guarantee a good compost quality and reduced emissions (Keener et al. 1992). As composting is primary a microbial process, the main function of the composting reactor will be the realization of optimal environmental conditions for the microbial population (Finstein 1980). To define these optimal conditions the dependence of the composting rate on environmental conditions, i.e. composting kinetics should be known.

Knowledge of only the optimum conditions is not sufficient. Optimal composting temperature can be as low as 45 oC (Finstein & Hogen 1992). For pathogen reduction an elevated temperature well above 45 oC is necessary (Bollen 1992; Farrel can be as low as 45 oC (Finstein & Hogen 1992).

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The best way to achieve this is via mathematical modeling of the kinetics of the process. Although for design purposes there is a pressing need for a composing kinetics model, at present there is no standard model.

Topic of this review is the mathematical modeling of composting kinetics. The topic is treated from a more general perspective of systems science. Models described in literature will be categorized according to their model building strategies.

Two main strategies can be distinguished, the inductive strategy that is data based and the deductive strategy that is theory based. It will be argued that both strategies can not succeed in delivering a validated general kinetic model. A modified deductive strategy is proposed that might avoid the shortcomings of the currently used strategies. This strategy is exemplified by handling the temperature effect on composting.

2. MODEL BUILDING STRATEGIES

Aris (1978) defines a mathematical model concisely as ‘‘any set of equations that under certain conditions and for a certain purpose provide an adequate description of a physical system.’’ A physical system is an outlined part of reality whose properties one seeks to understand, in this paper the composting rate of a waste sample. A model contains basically two types of quantities, parameters that are constant in time and variables that vary in time.

An input variable is a variable that is not affected by other quantities within the model and that can be freely chosen (to some extent) or is imposed by the outside world. The output is a variable that is observed. A model building strategy describes the steps needed to build an adequate model for a given process.

A model building strategy is no strict methodology, it is more a set of guidelines that have proven useful. In literature many different sets of guidelines can be found. (Eykhoff 1974; Beck 1980; Spriet & Vansteenkiste 1982; Heij & Williams 1989; Keesman 1989; Beck 1993; Ljung & Glad 1994a; Reichert & Omlin 1997).

Figure 1 gives a schematic representation of the model building process based on the work of Heij and Williams (1989) and Eykhoff (1974). The figure is structured around the starting points and outcomes that are printed in italic in the text.

The starting point of the strategy lies in the phenomenon or process of interest, the theory about the process and the objectives of the modeling exercise. Modeling objectives influence modeling process during all phases. Typical modeling objectives are understanding, describing, predicting, controlling or optimising the process.

For instance, in modelling a composting process it is important to know whether one wants to have a model that just describes the rate of a specific waste or one wants to understand the processes that are occurring. In the case of describing the rate one might use an empirical model, while for understanding how various factors affect the rate one uses a mechanistic model.

Objectives are especially important when evaluating the resulting model. The process of interest in this paper is composting kinetics. Associated with this process is a body of more or less well developed theory that describes and explains the phenomenon.

Theory if available leads to a set of a priori concepts about the process. For instance, realising that composting is a microbial process leads to inclusion of the concept ‘‘microbial biomass’’ into the model. The choice for concepts is also influenced by the model objective. Based on the a priori concepts a model structure is defined, i.e. a collection of feasible models is constructed.

The strategy of deriving a model structure from theory is called the deductive strategy (classical modeling, white box modeling), where the theory takes a central place. However theory is not always available, or theory is deemed less relevant, in such a case a so-called inductive strategy (black box modeling) is followed.

Instead of deducting a model from first principles, a flexible model family (e.g. linear regression, difference equations with flexible order, etc.) is chosen as the model structure. The inductive approach tries to find the relationship between output and input.

3. INDUCTIVE COMPOSTING KINETICS MODELING

Composting kinetics is defined in this paper as a comprehensive set of equations (mathematical model) that describe the dependence of the composting rate on environmental factors over a range of practical interest.

The kinetic model to be developed should be able to predict the process rate in relation to the (actual) composition of the waste and (actual) conditions to which this waste is exposed in the reactor.

Starting point of any inductive kinetic model is the degradation of organic matter as this supplies the free energy to drive the process (Waksman et al. 1939; Godden et al. 1983; Finstein et al. 1985; Godden & Penninckx1987).

The other factors influencing the process rate are generally referred to as environmental factors. The most important environmental

3.1. Organic matter degradation modeling

The process rate is preferably expressed on the basis of a unit amount of waste and not of the total amount of the waste. Keener (1992) discusses this matter in more detail and proposes the following first order model:

$$\frac{dm}{dt} = -k(x_1, x_2, \ldots\ldots, x_n) \cdot [m - m_e] \qquad (1)$$

where m (kg) is the composting mass; k (h^{-1}) the composting process rate constant; xi the environmental factor e.g. temperature, oxygen, moisture, etc; t (h) the time; and me (kg) is the equilibrium mass, i.e. the residual mass after infinite composting time.

The model above is a state space model with m as a state variable. The output of the model is also m as this is the observation. The model has two parameters me and k. The latter parameter is the function of a number of exogenous variables or inputs. If the environmental factors remain constant in time, integration of the above equation directly leads to:

$$R = \frac{m - m_e}{m_o - m_e} = e^{-k \cdot (x_1, x_2, \ldots\ldots, x_n) t} \qquad (2)$$

where R (dimensionless) is the compost mass ratio.

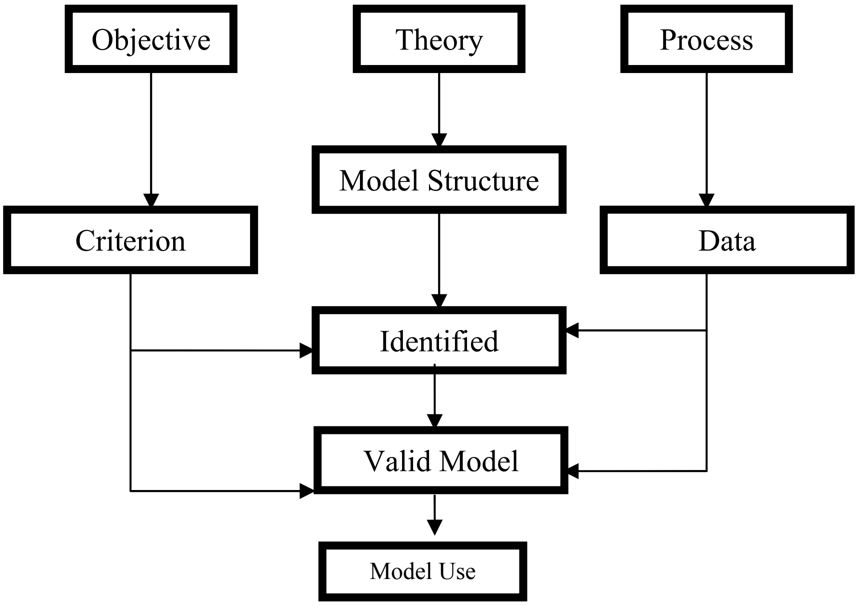

Figure 1. Schematic flow scheme of the model building process

The compost mass ratio changes from 1 at t =0 to 0 at t= ∞ and is a useful measure for the process progress and consequently compost stability. The value of the compost process rate constant k depends on the type of waste. In case of chicken manure the data of Keener (Keener et al. 1992) show that this model is applicable over a short time period (approx. 3 days), after such a period the k-value had to be updated, to reflect the changes in waste composition. In the case of yard waste the model is applicable over a much longer period once the peak activity has been reached (Marugg et al. 1993).

3.2. Environmental factor modeling

A number of kinetic models have been published in the literature about the dependence of the compost process rate constant k on environmental factors (Schulze 1961; Jeris & Regan 1973b; Jeris & Regan 1973a; Finger et al. 1976; Haug 1980; Whang & Meenaghan 1980; Cathcart et al. 1986; Nakasaki et al. 1987; Stombaugh & Noke 1996; Richard 1997). These models share the following multiplicative structure:

$$k(x_1, x_2, \ldots\ldots, x_n) = k_s \cdot f_1(x_1) \cdot f_2(x_2) \ldots f_n(x_n) \tag{3}$$

where k_S (h-1) is the composting process rate constant under standard environmental conditions;n the number of environmental factors; and f1,f2 the Environmental factor effect function.

The functions f describe the effect of a specific rate determining factor on the process rate constant. If the process rate is measured under standard conditions all functions have the value 1.

The most extensive model is still the kinetic model proposed by Haug (Haug 1980). This models takes into account the effect of temperature [T, _C], the gas phase oxygen content [O2, % vol.], the moisture content of the waste M, [kg water_(kg waste))1] and the free air space FAS, [m3 air_(m3 bulk waste))1]

An important assumption underlying the multiplicative model is the independence of the effects of the different environmental factors involved.

However, Richard and Walker (1998) and Richard et al. (1999) have shown that depending on moisture content, oxygen content and material, the optimal temperature varied from 52 to 64 _C.

The effect also depends on the extent of organic matter degradation, thus not only do environmental factors influence each other but also the changing composition of the waste influences the effect. Compared to the factors oxygen, moisture and temperature, the dependence of the rate on the waste composition has received little attention.

4. CONCLUSIONS

Inductive modeling approach limitations A distinct feature of the models used to date is that they are inductive models i.e. they try to relate directly the input (e.g. temperature) to the output, the composting rate.

Although these models give a good description of the observed kinetic dependencies, it is expected that the data-oriented approach will not yield a comprehensive kinetic model i.e. a model that embraces all major environmental factors including waste composition.

The following justification is given to substantiate this statement.

1. To investigate all environmental factors and their possible interactions a big experimental effort is needed. This is especially so because the heterogeneity of the waste calls for numerous replications.
For instance to determine the effect of oxygen and moisture on the optimal temperature Richard (1997) performed the experiments at three moisture levels, three oxygen levels and four temperatures. To achieve sufficient accuracy each combination was measured three times, yielding a total of 108 experiments. Trying to include two additional factors like pH and porosity in this scheme would give $3 \cdot 3 \cdot 108$ experiments, which gives a total of 972 experiments.

2. A number of factors (biomass, particle size) are expected to be important but can not be measured. For instance biomass can not be measured as no techniques are available for quantitative measurement in an organic waste matrix (Mitchell & Lonsane 1992). This makes it impossible to come up with an inductive model for these factors. As these factors tend to be variable, they constitute a source of variability when measuring the effect of other factors.

None of the aforementioned objections is of a principal nature, i.e. with sufficient effort and smart measurement techniques they could be overcome. Nevertheless taking into account the current measurement standards in composting the inductive approach seems to have reached its practical limit.

The lack of a theoretical framework for composting kinetics thus seems to be the main obstacle for further development of kinetics and hence a deductive model approach is needed to achieve further progress.

Current kinetic models are generally inductive models. The inductive approach seems to have reached its practical limit. The deductive approach seems therefore an additional fruitful direction to investigate composting kinetics. Care should however be taken not to develop models with nonidentifiable parameters, as deductive models of complex systems like composting contain many parameters.

To prevent this situation it is proposed that a model should be constructed with combined parameters, i.e. fewer parameters that are identifiable however still have a clear relationship with the basic parameters.

The advantage of this approach is that it enables to use information from existing knowledge (as represented by the basic parameters) with the information retained in the data (as represented by the identifiable combined parameters).

BIBLIOGRAPHY

[1] Kaiser J (1996) Modelling composting as a microbial ecosystem: a simulation approach. Ecol. Model. 9: 25–37
[2] Reichert P & Omlin M (1997) On the usefulness of overparametrized ecological models. Ecol. Model. 95: 289–299
[3] Stombaugh & Nokes (1996) Development of a biologically based aerobic composting simulation model. Trans. ASEA 39(1): 239–250