Dynamic Simulation of Closed Aerobic Composting Process of Empty Fruit Bunches

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COMPOSTING is a decomposition process that has attracted a lot of attention, particularly in Malaysia. In 2004, 381 palm oil mills in Malaysia generated about 26.7 million tonnes of solid biomass and about 30 million tonnes of palm oil mill effluent (POME) (Yaacob *et al.*, 2006). The use of empty fruit bunches (EFB) for various applications, as shown in Figure 1, has caused environmental problems and its utilisation is being explored without affecting the environment.

In the past, conversional processes such as the burning of EFB to produce energy and ash, which was later used as fertiliser, contributed to environmental problems (Baharuddin *et al.*, 2008). This was replaced by the mulching of EFB in fields, which resulted in methane production, one of the greenhouse gases. Due to the environmental problems resulting from both methods, aerobic composting has become a more reliable method for processing EFB and POME.

Figure 1: Empty fruit bunches from palm oil mill (http://earthcycle.com/blog/tag/palm-fiber/)

Figure 2: Final compost from EFB and POME sludge (http://www.ebgroup.upm.edu.my/research/biofertilizer/)

In composting, the decomposition rate is influenced by physical and chemical factors such as pH, moisture, aeration, C/N ratio and temperature. Composting is a complex biological process that also involves several types of microorganisms such as bacterial, actinomycetes, white-rot fungi and red-rot fungi. Microorganisms, in certain conditions, have the ability to convert raw substance into humic substance or compost, containing many nutrients, which can be used as fertiliser in agricultural fields (Figure 2).

Basically, aerobic composting requires a carbon source for the microorganisms to produce energy through oxidation. Microorganisms also need a nitrogen source to grow and reproduce more microorganisms in order to oxidise the carbon source. Oxygen is an essential element in the aerobic composting process. Water, at a sufficient level, is required to maintain the microorganisms' activity. If the water content is too high (>70 %), the composting process tends to become anaerobic.

The application of mathematical modelling in compost science and engineering is important to improve our understanding of the behaviour of the system, propose new theoretical concepts, predict its biological behaviour, and help in designing problems (Mason, 2006). The dynamic mathematical modelling has to be derived from both energy and mass balances.

gPROMS is a general process modelling system software used in the dynamic simulation of composting. gPROMS possesses simulation, optimisation and parameter estimation of highly complex process capabilities and can be adapted to both steady state and dynamic processes. gPROMS has been widely used for a variety of applications including pharmaceutical, food, petrochemicals, specialty chemicals, bioprocess and control. The composting process is a complex biological process that requires complex mathematical modelling, which includes physical and biological aspects that are interrelated to each other.

PROCESS MODELLING

The understanding of the dynamic process is essential for a bioprocess, to observe if it influences any change of conditions to be predicted. Dynamic models for the composting process are necessary to simulate the start-up process behaviour as well as the influences of perturbations

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of the system. Dynamic models of composting are very complex, combining algebraic and differential equations such as

(i) microbial growth kinetics (bacterial, actinomycetes, brown-rot fungi and white-rot fungi) with temperature, moisture, free air space and oxygen correlations,
(ii) substrate degradation models (carbohydrates, hemicelluloses, celluloses and lignin),
(iii) humic substance production model,
(iv) respiration models (CO_2 and O_2 generation/utilisation),
(v) thermal models and
(vi) water generation model.

Mathematical modelling of the composting ecosystem includes mass transfer, heat transfer and the conversion of organic matter into a humic substance and CO_2, and the model was adapted from Kaiser (1996) with some modifications. The batch bioreactor contains composting material as shown in Figure 3. The composting material consists of EFB and POME sludge. The material is aerated and mechanically agitated in order to keep it homogenous. Leachate may occur when the moisture level is high (for example >68%), and the generated leachate can be recycled to the bioreactor.

The composting process produces heat and increases the amount of saturated water vapour than that exhausted. To maintain the optimal moisture level (60% to 68%), the addition of water from POME can be controlled during the composting process (Figure 3). Only some bacteria are alive at the maximum temperature of 80°C, whereas other microorganisms stop growing at about 60°C. This temperature limitation is also considered in the mathematical modelling.

The dynamic mathematical modelling of substrate degradation (carbohydrates, hemicellulose, cellulose and lignin) as well as microbial growth has been improved in our work. The carbohydrates (sugars) are easily degradable compared to hemicellulose. However, it is more difficult to utilise cellulose for other processes; followed by lignin. According to Figure 4, in aerobic composting, bacteria are capable of degrading carbohydrates into composting material. Actinomycetes can also utilise carbohydrates as well as hemicellulose. Brown-rod fungi do not only degrade carbohydrates and hemicellulose, but also cellulose, whereas white-rod fungi can breakdown the complete range of substrates including lignin.

The mathematical modelling of substrate degradation also considers the conversion of hemicellulose and cellulose into carbohydrates, which is then utilised directly by all microorganisms. According to Kirk and Farrell (1987), lignin needs co-substrates to be degraded. If co-substrates (carbohydrates, hemicellulose and cellulose) are exhausted, the growth of lignolytic organism (white-rod fungi) and the degradation of lignin are prohibited.

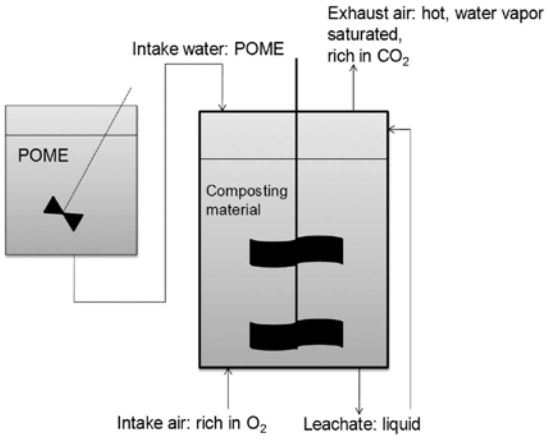

Figure 3: Proposed aerobic closed batch bioreactor system of composting

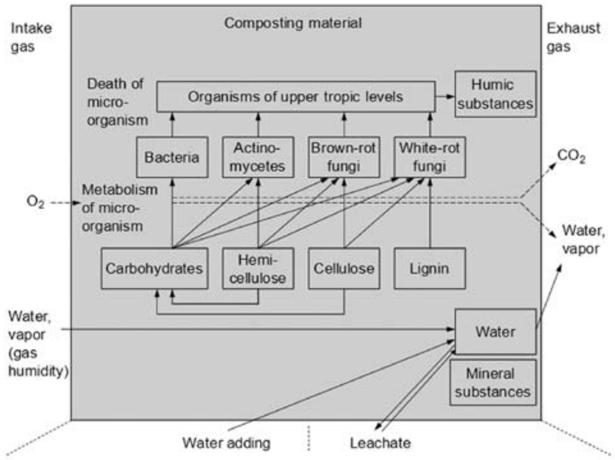

Figure 4: Substrate utilisation and microorganisms' metabolism in composting material (Kaiser, 1996, with some modifications)

EXPERIMENTAL DATA

In the presence of O_2, the metabolism of microorganisms produces energy, CO_2 and water. Kaiser (1996) assumed that the humic substance is produced from the organisms' death at the upper tropic level due to the low quality balances of CO_2 and heat. The upper tropic level consists of four parallel processes that are influenced by the substrate's concentration and temperature. To monitor the degradation of an individual substance, the composting sample can be analysed according to Gorring and Soest (1970).

For microbial growth, bacteria, actinomycetes, brown-rod fungi as well as white-rod fungi need to be analysed during composting. The other monitoring parameters include

(i) process temperature, mass and space of the composting material,
(ii) CO_2 level in the exhaust air and
(iii) water content of the composting material and volatile matter. To estimate unknown kinetic parameters simultaneously, all required experimental data can be set in the 'parameter estimations' entity of the gPROMS software.

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Table 1: Initial composition of composting material

No	Composting material (EFB+POME sludge)	Mass fraction
1	Carbohydrates	0.015
2	Hemicellulose	0.074
3	Cellulose	0.111
4	Lignin	0.074
5	Humic substance	0.000
6	Minerals	0.074
7	Bacterial	$7.40e^{-6}$
8	Actinomycetes	$2.96e^{-5}$
9	Brown-rot fungi	$1.48e^{-4}$
10	White-rot fungi	$7.41e^{-4}$
11	Water	0.670

Intake gas rate: 12 m^3/h
Ambient temperature: 30°C

DYNAMIC SIMULATION

gPROMS was used for dynamic simulation. The models are set using the conditions in Table 1. Composting material consisted of EFB and POME sludge, and the moisture content is set at around 65% during the process. If the moisture is below 65%, water from POME will be added into the composting material.

The degradation of individual substrate is shown in Figure 5. Sugars (carbohydrates) were utilised very fast and lignin seems non-degradable when all co-substrates are exhausted. The humic substance produced during composting increases due to the death of microorganisms at the upper tropic level. Figure 6 depicts the interrelation of substrate degradation in the presence of bacteria, actinomycetes, brown-rot fungi and white-rot fungi. The growth of bacteria reached the maximum level on the 11th day, and then gradually decayed due to depleted carbohydrate content. However, the growth of actinomycetes, brown-rot fungi and white-rot fungi were almost stable even though hemicelluloses and cellulose are completely utilised.

Figure 7 demonstrates the water flow rate due to the biological process (H_2O bio), exhaust to the outside of the bioreactor (H_2O exhaust) and addition of water from POME (POME adding), as well as the moisture content. The exhaust water rate increases drastically due to the increase in the amount of saturated water in composting material (when temperature increases). After the 23rd day, it decreases due to the lower amount of saturated water produced (when temperature decreases). Because the system is aerated continuously, it can cause a drop in the moisture content of the composting material. However, water from POME is added in order to maintain the optimal moisture content of the composting process in the range of 60% to 65%.

Figure 8 demonstrates the dynamic profile of total mass and dry-mass of composting material. The mass of composting material decreases due to the degradation of carbohydrates, hemicellulose, cellulose and lignin to produce humic

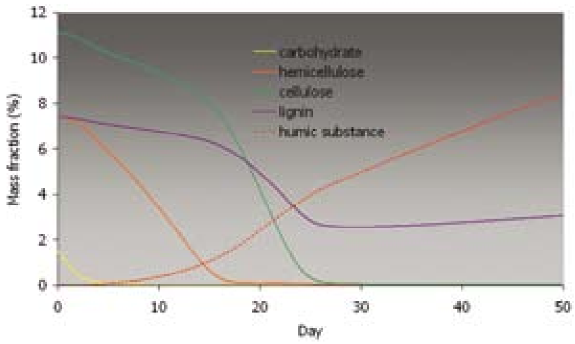

Figure 5: Dynamic profile of individual substrate and humic substance during composting simulated by gPROMS

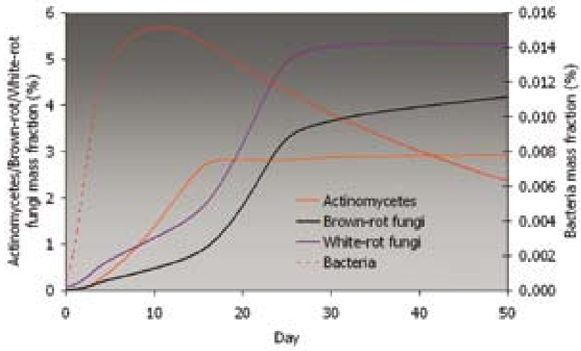

Figure 6: Dynamic profile of microorganisms during composting simulated by gPROMS

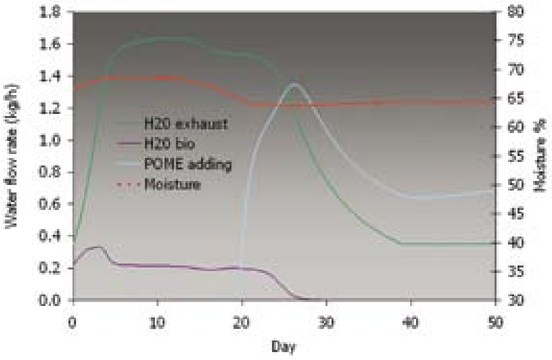

Figure 7: Dynamic profile of water flow rate and moisture content during composting as simulated by gPROMS

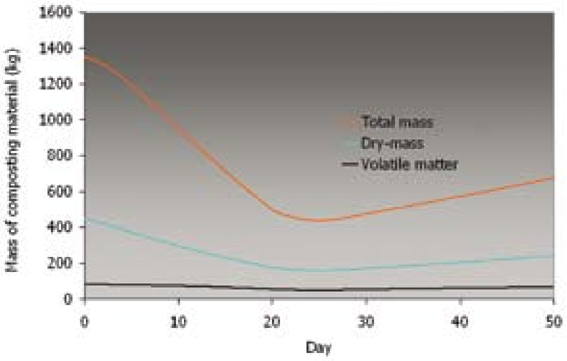

Figure 8: Dynamic profile of total mass, dry mass and volatile matter during composting as simulated by gPROMS

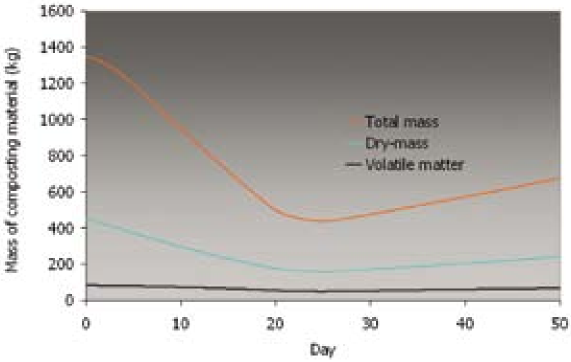

Figure 9: Dynamic profile of oxygen, carbon dioxide and temperature during composting as simulated by gPROMS

substance. Until day 23rd, the mass of composting material gradually increases because of the addition of POME (as shown in Figure 7), which consists of a low amount of substances (4%: carbohydrate, hemicellulose, cellulose and lignin). Carbohydrate, hemicellulose, cellulose and lignin from POME are directly utilised when added to the composting material, thus humic substance continues to increase after day 23rd (Figure 5).

The O_2, CO_2 and temperature profile can be seen in Figure 9. Temperature is a very important parameter as it indicates the bioactivity level of the microorganisms. When the substrates are exhausted, the metabolism of the microorganisms stops and the temperature decreases gradually. At the same time, the utilisation of O_2 to produce CO_2 will also stop. The dynamic simulation of the composting process has some advantages, including:

(i) Prediction of the composting process (changing air inlet flow rate, reactor size, capacity, *etc.*)
(ii) Scale-up process
(iii) Process troubleshooting
(iv) Process feasibility
(v) Process improvement and optimisation

CONCLUSION

The application of fundamental compost engineering is essential for an efficient composting process. Dynamic simulation is useful to predict various compost systems, including process variables and implications for design and operation. However, composting involves not only theory and practice, but also elements of art. The quality and stability of the final product is mostly judged by the operator on appearance, touch and smell. ■

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