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Heat Recovery Technologies from Aerobic Bio-degradation: from Theoretical Finding to Modeling Results

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Abstract

It is common knowledge that complete biomass aerobic (in the presence of oxygen) degradation releases the same amount of energy that was captured in the biomass cells during photosynthesis or feeding. If the bio-degradation process is managed in a way that there is an optimal moisture, oxygen and feedstock supply, a kind of bacteria – thermophilic – proliferate, and their metabolism processes can increase the biomass temperature to over 70 ^{o}C. However, the optimal temperature for these bacteria is about 60 ^{o}C, so the excess heat energy should be removed and could be used for heating. The purpose of this paper is to present a review of state of art of available technologies and research papers for heat recovery from aerobic bio-degradation. Modelling methods will be applied for theoretical investigation. The conclusions are that heat recovery from aerobic bio-degradation is not a well explored field and only a few papers are available where a prototype or experiments are presented exactly on heat recovery technologies from bio-degradation. On the other hand the process of biodegradation is well explored and some of the technologies for composting purposes use heat recovery to accelerate the process of composting. In the future it would be advisable to research and experiment in order to make prediction models for bacteria behaviour if the parameters are changed, and be able to automate the process.

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1. Introduction

The basics of biodegradation is energy release and mineralization of organic matter. Energy and organic mass initially comes from enclosing the Sun's energy and inorganic substances. The basic reaction for this is the photosynthesis reaction showed in equation (1).

$$6CO_2 + 6H_2O + energy => C_6H_{12}O_6 + O_2 \qquad (1)$$

where carbon dioxide and water with the help of sun energy in plant cells are transformed to glucose and oxygen.

After the organism is dead, it starts to decompose with a help of microbiota. If sufficient oxygen content is available aerobic decomposition takes place and basically a reversed photosynthesis reaction happens. Compost processing is the decomposition of biomass by aerobic microorganisms, which live in the air or in the surface of materials by nature. Some composts yield heat over 70 degrees Celsius in fermentation process. That exothermic reaction produces a considerable amount of heat, which could be a potential heating source. If the biomass amount is sufficient and the biomass flow is regular, then it is possible to make a system for heating or hot water purposes[1,2].

Traditionally compost has been used to improve soil fertility, today, composting is also used to reduce the volume of waste and turn organic waste into valuable end products as landfill siting becomes more difficult and expensive[3]. Compost utilization could decrease environment load and be promising as an alternative energy source. Direct combustion is a popular energy transformation process but not so appropriate for materials with high moisture content. In addition, direct combustion emits harmful materials such as tar, CO and NO_x in the exhaust gas, also a flame is present and temperatures are high which causes more risks than composting the biomass. The biodegradation process is difficult to control due to thermophilic microorganisms high sensitivity to parameter change, biomass waste is easy to get and sometimes even for free, and biodegradation helps to resolve the biological waste utilization problem.

Since the biodegradation process is as old as life on Earth itself, we should make a distinction – this paper will talk about effective use of biodegradation in order to utilize waste and get effective heat from the biodegradation process. There are several important parameters that influence the biodegradation process: oxygen content, moisture content, C/N proportion in the waste and temperature.

In the composting process, microorganisms dissolve easily degradable biomass and achieve living energy using metabolism activities. The composting process is a complex system relating to microorganisms. The composting process can be divided into four phases based on ambient temperature: a mesophilic phase (phase I), a thermophilic phase (phase II), a cooling phase (phase III), and a maturation phase (phase IV). In phase I, the compost mass is at ambient temperature and may be slightly acidic. In phase II the temperature exceeds 40 °C, the mesophiles decline, and degradation is dominated by the thermophiles: bacteria from bacillus genospecies[4] and fungi secrete extracellular enzymes which break down polymers such as cellulose. As readily degradable substrates decline, heat loss exceeds metabolic heat generation and phase III, the cooling phase, is initiated. Phase IV, compost maturation, is critical to its agronomic use because nitrification bacteria that need lower temperatures, can react with nitrogen compounds[5].

Mathematical modelling of aerobic degradation process is useful and necessary tool to correctly design a composting system and predict its performance under different operating conditions. Composting modelling has been widely reported in the literature. Hamelers[6] and Mason[7] offered a complete review on the different aspects of modelling, such as the various kinds of kinetic models, the influences of common variables including temperature, moisture and porosity, and model sensitivity analyses. In the works of Johnson[8], Matsuda[9], Selegovskis[2], Zhang[10] C decrease in biomass during composting has been modelled from experimental data, but the temperature is not kept constant, so the degradation rate is not directly valid for the purposes of the model proposed in this paper. In the

work of Villaseñor[11] C degradation rate in constant temperatures has been found. Composting modelling is not a difficult task. Wastes used in composting processes are no homogenous and cannot be characterised as pure organic compounds, and their composition is usually indicated by carbonaceous fractions with different biodegradation rates[11].

Regarding thermophilic biodegradation process there are also some research made, for example, Kim[12] and Ugwuanyi[13], but is lacking an information about microorganisms' behaviour regarding eating rate at constant optimal conditions that is needed for energy recovery modelling ad prediction.

2. Aerobic thermophilic heat recovery: state of art

The possibilities for using the thermophilic aerobic process for waste treatment are mentioned already in Couillard[14] where it was used for the treatment of meat processing industry's effluents.

In Le Jiamin[15] was proposed round shaped stationary compost fermenter with blades inside for stirring and mixing the biomass, and made some theoretical and experimental calculations on energy release during the process. A technology for space heating with compost heat[16] proposes a solution with water pipes installed at the bottom of the reactor for optimal temperature maintenance in reactor and excess heat utilization for heating, but very little information is found about heat recovery from aerobic biodegradation to utilize the heat for housing heating purposes; some more examples are found in Plume[17], Selegovskis[2] and Vining[3] works. However, there are more solutions proposed, in which biologically generated heat is used in plant station for preheating for faster biodegradation such as in the research of Bartkowska[18] for sludge and in patent of Jiang[19] about pipe heat exchanger for heating biomass, two stage air supply system in patent of Feng[20]. In big industrial type biodegradation reactors for utilizing the waste it is common maintaining a temperature that is suitable for thermophilic bacteria, for example, in Matsuda[9] and Couillard[14]. Couillard[14] in their study maintained their reactor in the thermophilic range by using heaters. In the work of Toriyama[1] compost heating system solution using magnetic field for better aeration is proposed. In the patent of Stubborn[21] system for using fermentation afterheat for efficient air drying is proposed.

Mostly the waste material for composting reactors are manure, food waste from industry and sewage sludge like in Couillard[14], Matsuda[9], Bartkowska[18], Le Jiamin[15].

3. Model inputs and outputs

In the following paragraphs all the most important model parameters – moisture, oxygen, feed, temperature, decomposition rate will be described. This model is not considering ash content and effect of particle size.

3.1. Moisture

Below a moisture content of 35 to 40%, decomposition rates are greatly reduced; below 30% they virtually stop. For most compost mixtures most literature recommends a moisture content of 50%-60% by weight for optimal composting conditions. Because composting is usually a drying process (through evaporation due to microbially generated heat), starting moisture contents are usually in this upper range[22]. Also Angima[23] agrees with this proposing optimal moisture content of40-65%. The lower limitation in found in the work of Vining[3] moisture content equal to or greater than 30% is advised, but the upper limitation of not more than 60% in Le Jiamin[15] is found. Based on literature review, we used moisture content of 50% in our model.

3.2. C:N ratio

Nitrogen is a crucial component of proteins, and bacteria, whose biomass is over 50% protein. When there is too little nitrogen, the microbial population will not grow to its optimum size, and composting will slow down. In contrast, too much nitrogen allows rapid microbial growth and accelerates decomposition, but this can create serious odour problems as oxygen is used up and anaerobic conditions occur. In addition, some of this excess nitrogen will be given off as ammonia gas that is a potent greenhouse gas in the same time allowing valuable nitrogen to escape.

Carbon is both an energy source, and the basic building block making up about 50 percent of the mass of microbial cells, and also crucial for optimal composting process[22].

For most materials, a C/N ratio of about 30 to 1 (by weight) will keep these elements in approximate balance[22]. Broader limitation are found in Angima[23]: from C:N ratio of 25:1 to 40:1. Based on this information for our model purposes C:N ratio of 30 was used. The right nitrogen content in a form of NH_3 was calculated based on the total C input. It was assumed that all the NH_3 would turn into NH^{4+} and OH^+, that is ammonium solution and no nitrogen leaves with the exhaust gases.

3.3. Temperature

The works of Tremier[24], De Guardia[25] and Jiang[19] is reported optimal T values of 50 to 65 °C, and inactivation temperatures of more than 70 °C Value difference could be related to the type of micro-organisms that are involved in degrading each biomass type[11]. Bacteria proliferate at higher temperatures and are more likely to degrade sugars, proteins and starch from the readily biodegradable carbon fraction; on the other hand, fungi have lower optimal temperatures and are the main group of micro-organisms involved in the degradation of lignocellulosic materials[26]. The research of Bartkowska[18] reported temperature of 65 °C as a limit value causing the cooling system to turn on for sludge system.

Based on the available information in literature we chose a constant 60 °C temperature to be optimal for process modelling since it could be the temperature where microorganisms have the biggest digestion and thus energy release power, as well as according to Barton[27] as the temperature of the composting increases to about 60 °C, the temperature destroys viruses, human pathogens and weed seeds.

3.4. Decomposition speed

A lot of models about C decline rate are available, for example, Johnson[8], Matsuda[9], Selegovskis[2], Zhang[10]. But mostly they are from processes where the temperature is not maintained constant, but is just consequences of decomposition speed, which is why they are not suitable for our situation. In the work of Villaseñor[11] C decrease model for constant temperatures is available, and that was used as a base for calculating the energy release rate and power in our case. From the data of Villaseñor[11] the equation (2) was gained for C (% in dry biomass) decrease trend:

$$C/C \ initial = -0,065ln(t) + 0,4497 \tag{2}$$

where t is time in days

3.5. Model reaction equilibrium

The organic material to be composted is usually a heterogeneous matrix with different components and particle sizes; it may contain many simultaneous reactions and mass transfer processes between the solid, liquid and gas phases[11]. That is why for this work model the biomass is simplified to only containing glucose $C_6H_{12}O_2$ as a representative of organic compounds, because it is fairly simple to understand and model the reaction equilibrium and for this simplified model the precision is satisfactory. The glucose was selected also because it is the basic element of the photosynthesis reaction (see eq. 1.1.) and glucose is the most common substrate used for studying heterotrophic metabolisms. Most aerobic organisms oxidize glucose completely by the following reaction equation (3)[28]:

$$C_6H_{12}O_6 + 6O_2 => 6CO_2 + 6H_2O + energy \tag{3}$$

Thermodynamically, the complete oxidation of one mole of glucose should yield approximately 688 000 cal; the energy that is not conserved biologically as chemical energy is liberated as heat 308 000 cal per glucose molecule[28],

that gives us about 16 MJ energy from a kilogram of glucose, this value was also used in the calculation in this paper.

The ash content was excluded from the model, since we used pure glucose and assumed complete oxidation of it, however ash should be considered in a real biodegradation process.

In the table 1 is shown main reaction input and output masses that arise from the fact, that at the beginning there is 250 kg of dry glucose, we assume that inlet air needed for glucose reaction is dry, and water is added to glucose so that 50% of total mass. Ideal gas equations were used to find the volumes of exhaust gases and theoretical air content.

Table 1. Model basic inputs and outputs based on glucose reaction and C:N ratio of 30

Input		Output	
C6H12O6, kg	250	CO2, kg	366
O_2, kg	266	CO_2, kg	366
N_2, kg	877	N_2, kg	877
V^o (theoretical air needed for reaction), kg	1144	Exhaust $CO_2 + N_2$, kg	1244
H_2O (50% add to glucose), kg	250	Water vapour in exhaust, kg	175
NH_3 (for right C/N ratio mass)	4,17	H_2O, kg (glucose reaction product)	150
N (in NH_3) in, kg	3,33	H_2O, kg (from add in)	250
C (in glucose), kg	100		

4. Modelling results

The main stress in the model was on the energy output since we wanted to understand how much energy and how fast can we theoretically get it out if the thermophilic aerobic biodegradation process. In table 2 the theoretically needed energy (without losses) for preheating together with process efficiency can be seen. The preheating effect on the available useful energy was calculated from attributing preheating energy to total inlet glucose energy due to assumption that the reaction is ideal and glucose mineralizes totally.

4.1. Preheating energy

Since one of the model assumptions was that in optimal temperature (60 ^{o}C) the biodegradation process is the fastest, we needed to consider the need of preheating the biomass (glucose), the added water and air to this optimal temperature from ambient air temperature of 0 ^{o}C, which was assumed to be an average temperature in the heating season in Latvia.

Table 2. Energy needed for preheating 0-60 ^{o}C and efficiency

Energy for dry air heating, MJ	69,11
Energy for added water heating, MJ	63, 01
Energy for glucose preheating, MJ	18,58
Total energy for preheating, MJ	151,98
Energy content in 250 kg glucose, MJ	4000
Efficiency η (preheating/glucose energy)	96%

4.2. Energy recovery from exhaust gases

Another important consideration for modelling is water vapour in exhaust gases. It is assumed that the reaction products are 100% saturated with water vapour. Since the water vaporization takes a lot of energy. For 60 ^{o}C equation (4) gives a solution of 2360 kJ/kg:

$$Cp_{wv} = 0{,}0779T^2 - 47{,}494T + 45089 = 2360 \qquad (4)$$

where Cp_{wv} is specific water vaporization energy, kJ/kg and T is vaporization temperature, ^{o}C.

The warm exhaust gases also have some energy to carry away, so the model considered heat regeneration from water vapour condensation and cooling the exhaust gases. Table 3 shows energy calculation results concerning condensation and cooling with the consequent process efficiency increase with lower cooling temperatures. The model looked at possible cooling in the temperature interval from 60 to 0 ^{o}C with a step of 5 degrees, for model simplification purposes assuming that vapour condensation happens momentarily in concrete temperature not gradually cooling the gas every 5 ^{o}C. For example, if cooling happens from 60-50 ^{o}C then condensation happens on 55 and 50 ^{o}C not on all temperatures between gradually. This assumption gives some mistake in the final energy calculations but is supposed to have little influence and of little importance, therefore neglected here. For calculating the vapour content in the exhaust gases an online Vaisala Humidity calculator (Vaisala 2006) which is a software tool that provides an easy way for solving humidity conversions from one humidity parameter to another. It can also be used to calculate the effect of changing ambient conditions. The calculation took into consideration the CO_2 and N_2 mixture molecular mass to output the max possible water vapour (saturation) mass in the gas at a given temperature.

Table 3. Energy recovery and process efficiency in cooling

Exhaust gas temperature ^{o}C	Cooling liquid water (including condensed water) MJ	Water vapour condensation MJ	Cooling water vapour MJ	Cooling exhaust gas MJ	**Total MJ**	Process efficiency after energy recovery %
0	99,46	402,98	0,01	73,64	**576,09**	100,3%
5	90,10	398,57	0,02	67,50	**556,19**	99,8%
10	80,96	392,53	0,02	61,37	**534,88**	99,2%
15	71,95	384,35	0,03	55,23	**511,56**	98,7%
20	62,92	373,38	0,04	49,09	**485,43**	98,0%
25	53,81	358,77	0,06	42,96	**455,60**	97,3%
30	44,87	339,46	0,08	36,82	**421,23**	96,4%
35	35,98	314,05	0,11	30,68	**380,82**	95,4%
40	27,30	280,69	0,14	24,55	**332,67**	94,2%
45	18,91	236,88	0,19	18,41	**274,38**	92,7%
50	11,25	179,18	0,25	12,27	**202,95**	90,9%
55	4,73	102,66	0,33	6,14	**113,86**	88,7%
60	0	0	0	0	**0**	85,9%

At 60 ^{o}C water vapour saturation or mixing ratio is 140,75 g/kg dry gas, which gives a total of 175 kg in 1244 kg CO_2 and N_2 mixture. For vaporization of these 175 kg is 413 MJ of energy needed. And that leaves 225 kg of liquid water (from add in in the beginning) that can't evaporate due to already saturated exhaust gases. And this liquid water recovered cooling energy is also considered. As the cooling temperature goes down, more and more vapour condenses and becomes liquid that is also summed to the original 225 kg of liquid water, and cooled to the given temperature. The 60 ^{o}C value row in the table represents efficiency if now cooling is done. An assumption of

relative humidity being 100 % at every given temperature. In reality humidity could be less, so in the table 3 the worse scenario with lowest efficiency is showed.
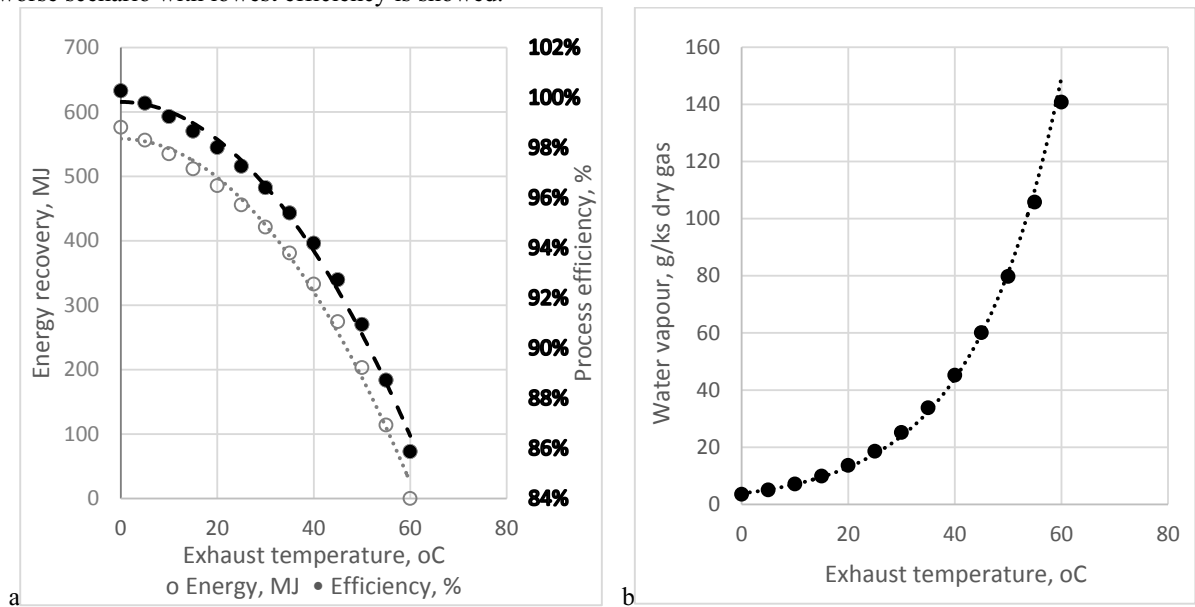

Fig. 1. (a) Energy recovery and process efficiency dependence on exhaust temperature with trend lines (b) Water vapour maximal mass (saturation) with trend line

In the Fig.1(a) is energy recovery potential from condensing water vapour showed that is based on the water vapour saturation data[29] in relative humidity of 100 % circumstances. In this case process energy efficiency η was calculated from equation (5):

$$\eta = 1 - (Q_l / Q_g) \tag{5}$$

where Q_l, MJ total losses, consisting of preheating energy (that after reaction transforms into exhaust losses) and water vaporization energy; and Q_g, MJ is glucose energy content in 250 kg.

And in Figure 1(b) is water vapour saturation mass in dependence with temperature given. It can be seen that cooling to lower temperature region (0-20 ^{o}C) gives proportionally very little energy recovery to compare to the highest temperature region (35-55 ^{o}C). These results are connected to vapour content in the gases – the lower the temperature, the lower maximal vapour content. It was calculated that without any cooling we lose 413 MJ or 115 kWh due to water vaporization and with 152 MJ or 42 kWh spent for preheating reaction products it makes 565 MJ or 157 kWh of total process loses or 14% of total input glucose energy. It means that the process efficiency without cooling is 86%. It can be seen that even cooling of 5 ^{o}C (from 60-55 ^{o}C) increases total efficiency to 89% and gives energy recovery of 114 MJ or 32 kWh; cooling of 10 ^{o}C (from 60-50 ^{o}C) gives efficiency of 91% and energy recovery of 203 MJ or 56 kWh. The maximum possible efficiency in given temperature range gives cooling to 0 ^{o}C: 100 % and energy recovery of 576 MJ or 160 kWh.

4.3. Biomass decrease and energy release rate

The last part of modelling was carbon decrease and following energy release calculations. The decrease rate was based on Villaseñor's[11] experimental data for biodegradation process in constant 60 ^{o}C. In his work two different kinetic models were used to fit the carbon mineralisation curves: the 2C model, which considers two organic fractions (biodegradable and non-biodegradable), and the 3C model, which considers three fractions (easily biodegradable, slowly biodegradable and non-biodegradable). The 2C and 3C simulation profiles were quite similar

in all cases for much of the process duration; the differences between the profiles only occurred after the end of the thermophilic stage, so it was decided to use 2C model results because the main interest of our modelled processes is rapid degradation stage in the thermophilic range.

The resulting C decrease in the biomass due to mineralization to CO_2 together with released energy and trends are shown in Fig. 2. Energy release was calculated from total available energy content in glucose (4000 MJ in 250kg) taking into account the percentage (and) rate of C mineralization as a representative of glucose oxidation reaction rate.
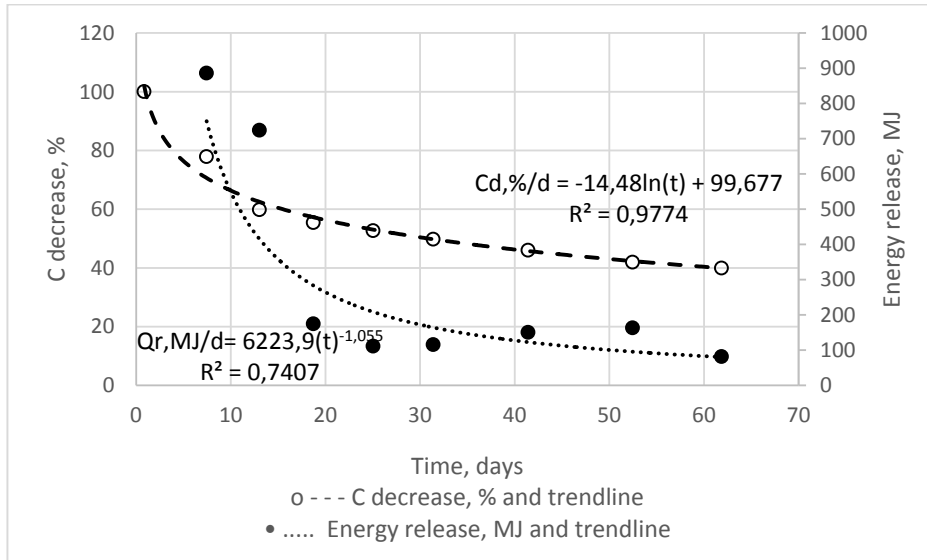

Fig. 2. Biomass decrease and energy release in time with with matching trendlines, equations and correlation coefficient R_2

From the work of Villaseñor[11] was found the carbon decrease rate Cd, %, equation (6) with very high correlation coefficient R^2 of 0.98.

$$C_d = -14,48ln(t) + 99,677 \qquad (6)$$

where t is time in days

Using the C decrease rate was then equation (7) found for describing energy release rate Q_r, MJ/days according to C decrease. The correlation coefficient R2 is 0.74 which is satisfactory for using the formula in calculations.

$$Q_r = 6223,9(t)^{-1,055} \qquad (7)$$

where t is time in days

In Figure 2 it can be seen that fastest energy release and following biggest power (over 1 kW) is observed at the beginning of the process. And the activity starts to decrease gradually due to lack of bacteria feeding. The optimal feeding rate therefore should happen regularly in the fast phase of degradation to provide the biggest power and fastest degradation process. In Le Jiamin[15] the average biomass deduction rate is 2.4%/day for 7 day experiment time. That gives around 17% decrease in 7 days which is comparable with 22% in Villaseñor[11].

During more than 60 days in Villaseñor's[11] experiment, only about a half of available C was degraded. Actually the process could be faster and the degree of degraded biomass faster than shown in the Figure 2, because in Villaseñor's[11] work biomass moisture content and C:N proportion was far from optimal, the process automatization could also contribute to faster degradation. Also in the work of Selegovskis[2] where the proposed energy power was about ten times bigger than the one calculated from Villaseñor[11].

5. Conclusions and discussion

As found in literature, there is much information available about the composting process, starting with overall process description to serious mathematical modelling. But in the same time not so much literature has been found on the thermophilic composting process alone without other process stages, and about thermophilic bacteria behaviour and biomass degradation rate in constant temperature. The thermophilic process is a matter of future studies to better understand the energy potential. There are also a lot of different industrial composting solutions, but only few concentrate on the thermophilic process and recover heat energy, which is also mainly to heat the biomass inside the reactor and fasten the composting process, and almost no information has been found about using composting to get useful heat. So the modelling results in this paper could be useful as a simplified basis to understand the energy recovery potential and available power from thermophilic biodegradation.

The conclusion is that the thermophilic biodegradation process is potentially perspective for heating purposes as suggested by the literature review and model calculations for energy recovery from biomass degradation.

Further research and experiments in a real bioreactor are needed to verify model calculations and adjust them, as well as make the model closer to real working conditions and take into consideration ash content, heat exchange calculations and parameters for cooling the exhaust gases, as well as different real biomass mixtures and their chemical content. But for approximate calculations to predict the needed air supply to the reactor, reactor volume and other reactor parameters the basic model proposed in this paper is suitable.

There is a discussion about reasonable exhaust cooling and vapour condensation temperatures and the real technological solution to gain the low potential heat since the little temperature difference mean slow heat exchange. Even though exhaust cooling under 20 ^{o}C or less gives a max process efficiency of 100 % and recovers 576 MJ or 160 kWh (cooling to 0 ^{o}C), it seems unreasonable thing to do, because the energy recovery is very little compared to higher temperatures, but the cooling process to such low temperatures is complicated. Efficiency difference between cooling to 20 and 0 ^{o}C is only 2.7 % while between no cooling and cooling to 40 ^{o}C the difference in efficiency is 8.32 %. Further calculations and research is needed to find the most appropriate cooling scenario. It probably is wise to cool the exhaust in big industrial reactors to lower temperatures due to more technological possibilities but not for decentralised household heating purposes since the reactor itself would probably need a bigger space than conventional reactors for better efficiency, and even more with a big heat exchanger.

There is also further research and experimentation needed to evaluate biomass degradation rate if optimal operating parameters are set.

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