Numerical Modeling of the Biodrying Process of the Organic Fraction of Municipal Solid Waste

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Abstract

Biodrying is an aerobic process during which the moisture content of waste is reduced while the degradation of organic waste is kept to a minimum. The main purpose of the biodrying process, as opposed to the composting process, is not to maximize the degradation of organic material, but to bring about the biodegradation of organic waste to an extent sufficient to produce biologically induced heat to dry the waste via evaporation.

The present research was an attempt to numerically model an aerobic bio-oxidation (biodrying) process based on relevant experimental data published in the literature. Moisture content removal and generation of carbon dioxide and ammonia during the biodrying process were examined. Furthermore, the potential of the biodrying process to produce a high quality refuse-derived fuel (RDF) product is discussed.

Given its simplicity, the numerical model used in this study did not take into account many important aspects of the biodrying process. However, its usefulness as a first approximation of the real biodrying process, was confirmed.

Keywords: biodrying, mechanically and biologically treated waste, moisture content, lower heating value, refuse derived fuel, RDF quality

1. Introduction

Biodrying is an aerobic process during which the moisture content of waste is reduced, while the degradation of organic waste is kept to a minimum. The main purpose of the biodrying process, as opposed to the composting process, is not to maximize the degradation of the organic material, but to bring about the biodegradation of organic waste sufficiently to produce biologically induced heat in order to dry a waste matrix via evaporation.

According to Velis et al. [1], the minimum moisture content below which the biodegradation process is inhibited has not been identified. However, from composting studies, it is evident that at moisture contents below 20% (w/w), very little or no microbiological activity occurs [2]. Therefore, achieving final moisture contents that are significantly lower than 20% (w/w) through biodrying only is unlikely.

Furthermore, by decreasing the moisture content within the waste mass, and by keeping the degradation of organic waste during the biodrying process to a minimum, the lower heating value of biodried waste increases. Thus, the biodried waste is much more suitable for use as refuse derived fuel (RDF).

The biodrying process can be described with the following chemical equation:

$$\mathrm{C}_n\mathrm{H}_a\mathrm{O}_b\mathrm{N}_c + \left(n + \frac{a}{4} - \frac{b}{2} - 3\frac{c}{4}\right)\mathrm{O}_2 + \mathrm{H}_2\mathrm{O(l)} \rightarrow n\mathrm{CO}_2 + \left(\frac{a}{2} - 3\frac{c}{2}\right)\mathrm{H}_2\mathrm{O} + c\mathrm{NH}_3 + \mathrm{H}_2\mathrm{O(g)} \qquad (1)$$

where $\mathrm{C}_n\mathrm{H}_a\mathrm{O}_b\mathrm{N}_c$ is the chemical formula of the organic waste. From Eq. 1, it follows that organic waste, with addition of a sufficient amount of oxygen, will decompose into carbon dioxide, water, and ammonia. It also should be noted that during the biodrying process, liquid water, which is initially present in the waste mass in the form of moisture, does not enter into the chemical reaction but undergoes transition from liquid to gas phase because of biologically induced heat.

Research regarding biodrying processes at small scale (laboratory scale) is widely available. For example, Adani et al. [3] examined the influence of biomass temperature on the biodrying process of three trials (A, B, and C) at three different temperatures (70, 60, and 45 °C, respectively). The different temperatures were maintained more or less constant during the tests via airflow rate control. The authors found that biodrying and biodegradation were inversely correlated. Fast biodrying produced low biological stability and vice versa. The initial moisture content of all three samples was 41% (w/w). At the end of the biodrying process, the final moisture content for trials B and C were 25.9% and 19.5%, respectively. The removal mass ratios between volatile solid consumption and water removal were 1:1.59 for sample A, 1:3.29 for sample B, and 1:24.7 for sample C. Evidently, the reduction of volatile contents in sample C, with respect to the amount of evaporated water, was almost negligible. The process parameters applied to sample C provided energetically reach but biologically unstable product. Thus, sample C was suitable for use as RDF only immediately after the biodrying process. The process parameters applied to sample B also provided energetically reach but biologically more stable product, which, in case of necessity, can be temporarily stored for later usage.

Sugni et al. [4] conducted biodrying experiments on three samples (D, E, and F). The experiment on Sample D was conducted using the same waste and under the same process parameters as Sample C in the work published by Adani et al. [3], mentioned above. Comparison of the results obtained from Samples C and D revealed that repeatability of the tests was not achieved, although the negligible decrease of volatile organic matter in Sample D was in accordance with the earlier results obtained on Sample C in Adani et al. [3]. Sample E was taken separately and therefore had different characteristics with respect to Sample D. For example, the initial moisture content of Sample D was 41% (w/w), whereas the initial moisture content of Sample E was 24.7% (w/w). Both samples were tested at 45 °C in order to achieve rapid biodrying as presented in Adani et al. [3]. The final moisture content of Sample E was 21.7% (w/w). Sugni et al. [4] showed that the lack of waste mixing and air supply in one direction only led to a final product with highly nonhomogeneous distribution of moisture content within the biodried waste mass.

Rada et al. [5] examined the biodrying process using small-scale pilot plant reactors. The reactors were assumed to work under adiabatic conditions. The weight loss (volatile solids + humidity extracted) was about 26% after two weeks of biodrying and 29% after four weeks of biodrying. Concerning humidity, the authors found that the average mass removal ratio between volatile solid consumption and water removal was 1:7.

Zawadzka et al. [6, 7] conducted five small-scale autothermal biodrying experiments on the organic fraction of municipal solid waste with initial moisture content higher than 80% (w/w). They found that after 10 days of biodrying, the initial moisture content decreased up to about 50%.

Shao et al. [8] examined drying efficiency under different ventilation modes. Samples were examined under three different ventilation modes (intermittent negative ventilation - IN, continuous negative ventilation - CN, and intermittent positive ventilation - IP). They found that, concerning humidity, the average mass removal ratio between volatile solid consumption and water removal was 1:5.4.

Bilgin and Tulun [9] examined volume and weight reduction due to biodegradation during the biodrying process on three samples at constant temperatures of 30, 40, and 50 °C. In addition to biologically induced heat, specific temperatures were maintained with additional (external) source of heat. The initial sample mass was 3 kg. After 13 days of biodrying, the volume content of waste was reduced to 12 – 32%, while the weight reduction ranged from 36.6 to 49.16%. The initial moisture content of the samples ranged between 48.49 and 50.00%, while the final moisture contents were 21.5%, 19.0%, and 4.5%, respectively, for the 30, 40, and 50 °C samples.

Dziedzic et al. [10] managed to reduce the moisture content of waste material through biodrying from an initial moisture content of 29.1% to final moisture content of about 20.1%. It should be noted that the examined waste material had, prior to biodrying, been submitted to the process of biostabilization, during which the initial moisture content of about 46.8% was reduced to 29.1%. However, biostabilized and subsequently biodried waste is not suitable for use as RDF because of its reduced lower heating value.

Tom et al. [11] examined the biodrying process in a pilot-scale biodrying reactor with a volume of 565 cm^3. The initial moisture content of synthetically prepared waste material was 61.25% (w/w). During the biodrying process, which lasted for 33 days, the moisture content decreased to a final value of 48.5% (w/w). The authors also reported that higher water removal values could be achieved if the condensation of evaporated water is prevented. The cumulative weight loss achieved during the biodrying process was 33.94%.

In contrast to the research regarding biodrying at small scale (laboratory scale), research on biodrying at large scale is rather limited. Elnass et al. [12] conducted biodrying experiments on windrows 5 m wide, 2 m high, and 40 m long. The biodrying process lasted for three weeks. The piles were turned and mixed once a week, while the air supply was secured through aeration pipes installed beneath the windrows. Five trials during winter and summer seasons were performed. In total, the weight of waste decreased by 29% during summer and 35% during winter. On average, 24% of water and 9% of solid waste mass were removed. After three weeks of biodrying, the moisture content was reduced to between 30% and 45%. It remained unclear whether the moisture content was expressed on a wet or dry basis. The average removal mass ratio between volatile solid consumption and water removal was about 1:2.7.

The present research was an attempt to numerically model the aerobic bio-oxidation (biodrying) process based on relevant experimental data published in the literature. The decrease in moisture content along with the generation of carbon dioxide and ammonia during the biodrying process were examined.

Even though, because of its simplicity, the numerical model used in the present research did not take into account many important aspects of the biodrying process, its usefulness as a first approximation of the real biodrying process was confirmed.

Furthermore, the potential of the biodrying process to produce a high quality RDF product is discussed. According to Quaak et al. [13], to ignite a fuel and extract energy from an RDF product, its maximum allowable moisture content is 55% w/w.

2. Material and methods

For the purposes of numerical modeling, the brand-name (e.g., SuperPro Designer) software package was chosen. Within the software, the well-mixed (WM) stoichiometric aerobic bio-oxidation procedure was selected (Figure 1). This procedure is generally used to represent the transformation (e.g., bio-oxidation, chemical oxidation, hydrolysis, photolysis, nitrification, and sorption) of organic and other compounds in a WM basin under aerobic conditions. Any number of reactions in sequence can be specified by stoichiometry. This model performs rigorous calculations of volatile organic compounds (VOCs) for surface and diffused aeration systems, and can be used when the reaction kinetics are unknown or unimportant, but the mass stoichiometry is known.

As can be seen from Figure 1, the WM stoichiometric aerobic bio-oxidation procedure has two input and two output streams. The feed stream is used as an input stream of moist organic waste material. The gas input stream is used as an air/oxygen supply stream. The product output represents the biodried residual waste stream, whereas the gas output stream shows how much carbon dioxide, ammonia, and water vapor is produced during the biodrying process.

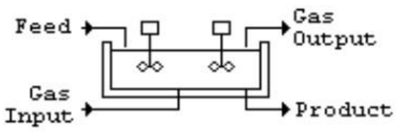

Figure 1. Schematic view of the well-mixed (WM) stoichiometric aerobic bio-oxidation procedure [14].

To model the biodrying process numerically with the selected procedure, it is necessary to perform the following tasks:

- Determine the representative chemical formula of the organic portion of the waste material
- Determine the percentage by mass of each chemical element from the determined representative chemical formula
- Determine the amount of oxygen/air that is necessary for the reaction to be 100% completed
- Adjust the reaction extent and water vapor parameters in order to achieve the targeted volatile solid consumption and water removal ratio
- Choose the initial waste mass and initial moisture content

2.1 Determination of the chemical formula of the organic portion of the waste material

The biodegradable portion of a municipal solid waste sample usually comprises organic matter, paper, and plastics, along with some percentage of components such as textiles, wood, or rubble. The typical component values (e.g., of paper, plastic, compostable, wood) of the solid waste sample used in the present numerical analysis (Table 1) were taken from [15].

Table 1. Typical component values of the biodegradable parts of municipal solid waste in Croatia

Component	Mass percentage [%] (mean value)
Compostable	42.1
Paper and cardboard	20
Wood	1.3
Textile	8
Plastics	12

As can be seen from Table 1, a representative sample of municipal solid waste from the Republic of Croatia has a biodegradable portion of about 83.4%.

The elemental composition (chemical formula) of the selected solid waste sample was determined in accordance with the procedure described by Tchobanoglous et al. [16] and Adeyinka et al. [17]. Based on this procedure, the representative chemical formula of the organic portion of municipal solid waste in Croatia is (2):

$$C_{37,67}H_{58,51}O_{20,58}N \quad (2)$$

2.2 Determination of the mass percentage of each chemical element specified within the representative chemical formula

For the obtained chemical formula (2), the mass percentage for each chemical element is shown in Table 2.

Table 2. Mass percentage for each chemical element in the representative chemical formula (2)

Chemical element	Percentage by mass [%]
C	52.94
H	6.9
O	38.52
N	1.64
Total	100

2.3 Determination of the amount of oxygen/air that is necessary for the reaction to be 100% completed

In accordance with Eq. 1, for the obtained chemical formula (2), the chemical equation of a 100% completed biodrying process with exact stoichiometric coefficients was established (3):

$$C_{37.67}H_{58.5}O_{20.58}N + 41.26O_2 + H_2O(l) \rightarrow 37.67CO_2 + 27.75H_2O + NH_3 + H_2O(g) \quad (3)$$

From Eq. 3, it can be easily calculated that 41.26 molecules of oxygen weighs 2.19234×10^{-27} kg and one molecule of organic waste material weighs 1.41926×10^{-27} kg. Therefore, for complete aerobic biodegradation of 50 kg of organic waste material, it follows that 77.37 kg of oxygen or 331.65 kg of air is needed.

2.4 Adjustment of the reaction extent and water vapor parameters in order to achieve the targeted volatile solid consumption and water removal ratio

Clearly, the biodrying process is never 100% completed. Not all biomass is transformed into carbon dioxide, water, and ammonia. Only a minor portion of the initial organic waste mass is transformed into these chemical compounds, while a majority of the input organic waste materials remains unchanged. Thus, to simulate only partial degradation of organic components during the biodrying process, the reaction extent option, which is available within the WM procedure, has been used as a limiting factor. Within the WM stoichiometric aerobic bio-oxidation procedure, the reaction extent option can be used to stop the chemical process at a specific percentage and establish stoichiometric equilibrium at that point.

Thus the reaction extent, in conjunction with percentage of vent emissions of water vapor, were adjusted in order to simulate laboratory (1:7) and field (1:2.7) volatile solid consumption and water removal ratios.

2.5 Selection of the initial waste mass and initial moisture content

The total sample weight used in the model was 100 kg, and the initial moisture content was set to 50% (w/w).

3. Results and discussion

Two numerical probes were run. To simulate laboratory conditions, the removal ratio of volatile solids and water was set to 1:7 in Probe 1. To simulate field conditions, the removal ratio of volatile solids and water was set to 1:2.7 in Probe 2. The targeted mass reduction for both probes was set to 25% of the initial mass [5].

The total waste mass in Probe 1 has been decreased by 24.36%, and the achieved percentage of water removal was 42.63%. The total waste mass in Probe 2 has been decreased by 25.64%, and the achieved percentage of water removal was 37.10%.

However, even though the percentages of water removal were rather high, because of simultaneous reduction of total mass (w/w) during the biodrying process, the moisture content of Probe 1 decreased from an initial 50% to 37.9%, whereas the initial moisture content of Probe 2 decreased from an initial 50% to only 42.3%.

In addition, gas stream data revealed that 3.43 kg of CO_2 and 0.035 kg of NH_3 were generated in Probe 1, whereas 8.00 kg of CO_2 and 0.08 kg of NH_3 were generated in Probe 2. Thus, it can be anticipated that under more realistic (large-scale field) conditions, the generation of carbon dioxide and ammonia will be approximately 2.5 times greater than that under optimal small-scale laboratory conditions.

Regarding RDF quality, Quaak et al. [13] presented the general relationship between calorific value of biomass (lower and higher heating values) and moisture content (Figure 2). For comparison purposes, lower heating value limits, one of the main RDF classification properties, was also added to Figure 2. As can be seen from Figure 2, Class 1 and Class 2 RDFs are almost completely dry fuels. Class 3 RDFs can contain up to 15% moisture content (w/w), Class 4 RDFs can contain up to 39% moisture content (w/w), and Class 5 RDFs can contain up to 73% moisture content (w/w).

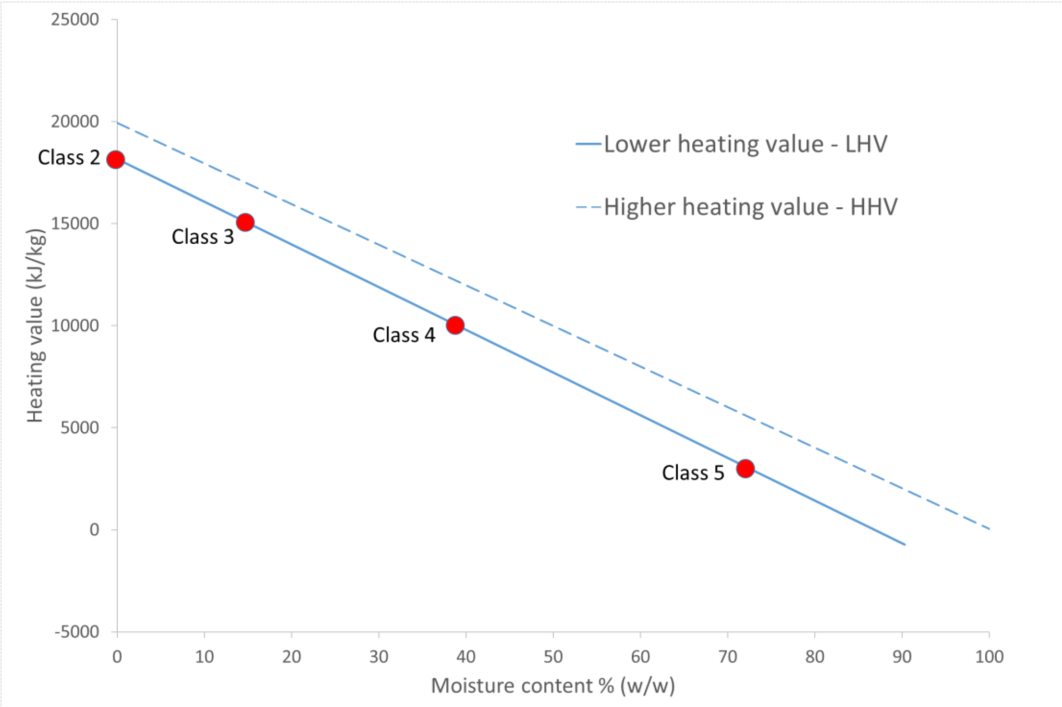

Figure 2. General relationship between the calorific value of biomass (lower and higher heating values) and moisture content [13], along with lower heating value limits (one of the main RDF classification properties) (red dots).

Because municipal solid waste materials usually have high moisture levels, it is evident that raw untreated municipal solid waste eventually can be classified as Class 5 RDF at best. Based on published data, along with the results obtained within the numerical model in the present study, it is anticipated that, after completion of the biodrying process, the RDF produced can be classified as Class 4, with a lower heating value close to 10,000 kJ/kg.

4. Conclusions

From the present research it can be noted that, on average, the ratio of volatile solid consumption and water removal lies within a range from 1:2.7 for field conditions up to 1:7 for laboratory conditions.

The removal ratio between volatile solids and water, with respect to the small differences in the final moisture contents obtained in Probes 1 and 2, does not seems to be a vital parameter. However, to obtain energetically reach product and to reduce the impact of the biodrying process on the environment as much as possible, it is crucial that the removal ratio between volatile solids and water during the biodrying process strongly favors water removal.

It is anticipated that under more realistic (large-scale field) conditions, the generation of carbon dioxide and ammonia will be approximately 2.5 times greater than that under optimal small-scale laboratory conditions.

Since biodegradation ceases at moisture contents less than 20%, it is highly unlikely that RDF material obtained via biodrying can be classified as Class 3 RDF or higher. To achieve RDF material of Class 1, 2, or 3, it is necessary to apply an additional (external) heat source.

With respect to the model used, the possible extensions are wide, including, for example, additions of an air conditioning system, a biofilter, an external heat source or any combination of such.

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