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2 Simultaneous Enects of An now and remperature increase on water removal in

3 drying

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18 ABSTRACT

Bio-drying MBT is a type of mechanical biological treatment (MBT) system, whereby 19 the aerobic biological process is first used to remove moisture, which is followed by the 20 mechanical separation to recover material and energy as a solid recovered fuel (SRF). Among 21 various parameters of this process, the simultaneous effects of airflow rate and organic 22 contents were examined in this study. A 25 L acrylic column reactor was filled with 23 simulated waste. Temperature and humidity of the air inlet and outlet were continuously 24 monitored, and CO₂ concentrations in outlet air were periodically analyzed to observe aerobic 25 biodegradation as well as metabolic water generation. Based on the data, the different water 26 removal contributions by airflow and biodegradation were compared and finally evaluation of 27

28	the inter-dependence of parameters and feedback effect in the bio-drying process was carried
29	out. While the biodegradation of organics induced a significant amount of water removal due
30	to increased temperature, high organic content has a negative effect on water removal by
31	generating metabolic water. Water removal by air replacement is greater than that associated
32	with temperature increases caused by biodegradation. However, excessive airflow rate can
33	terminate biodegradation by drastically lowered moisture content even though organics
34	remained.
35	
36	Keywords: Bio-drying, Organic content, Airflow rate, Water removal rate
37	

39 Introduction

Historically, most EU countries disposed of substantially mixed municipal solid waste 40 (MSW) in landfills without any type of pretreatment. High proportions of biodegradable 41 wastes have been discarded in landfills, which resulted in a need for long-term care to 42 manage the leachate and landfill gas emission caused from the biodegradation of organic 43 matter in the waste [1]. To deal with this issue, in the late 1990s, the European Commission 44 45 established the Landfill Directive (99/31/EC) [2], which required the diversion of biodegradable waste from landfills. In response to this directive, mechanical biological 46 treatment (MBT) systems have emerged to reduce the amount of biodegradable waste sent to 47 the landfill. A typical MBT system begins with mechanical separation of mixed MSW, which 48 is then followed by biological treatment to remove the organics and thermal treatment for the 49 remaining combustible fraction. The biologically and/or thermally stabilized residue from 50 these processes is sent to a landfill for disposal. Biogas is recovered when the organic fraction 51 is treated by anaerobic digestion, and energy is recovered as a solid fuel or through thermal 52 53 treatment, and dry recyclables are also recovered [3].

Bio-drying MBT is a type of MBT system, in which an aerobic biological process is first used to remove moisture, followed by mechanical separation to recover material and energy as a solid recovered fuel (SRF). SRFs can be burned in cement kilns or other cocombustion power plants as a fuel, which conserves the conventional energy sources typically used for those kinds of operations [4, 5].

In a previous study on bio-drying, the effects of several parameters were examined, including aeration (airflow rate (AFR), frequency), waste properties (waste type, moisture content, organic content (OC)), and bulking agents (type, mixing ratio) used to adjust the OCs or moisture contents. Among them, the AFR and OC have been considered as the primary parameters, and these two parameters were investigated in this study. The

simultaneous effects of the AFR and OC were also studied by Huiliñir and Villegas and
Colomer-Mendoza et al. [6, 7]. Huiliñir and Villegas used sludge from a wastewater
treatment plant used for the slaughterhouse and investigated the AFR (1, 2, and 3 L/min·kgTS) and OC by changing the ratio of the bulking agents (10%, 23%, and 33%), which
resulted in different initial moisture content values of 59%, 68%, and 78%, respectively.
Colomer-Mendoza et al. studied AFR (0.88 to 6.42 L/min·kg-TS) and the bulking agent ratio
(0% and 15% of mixture) in the bio-drying of garden waste.

Other studies have investigated AFR, OC, and other parameters. Adani et al. studied 71 AFR (0.1–0.4 L/min·kg-TS) in bio-drying of MSW [8], and Navaee-Ardeh et al. investigated 72 AFR $(25-75 \text{ m}^3/\text{h})$ in a bio-drying process that utilized paper and pulp mill sludge as the 73 feedstock [9]. While other studies have been conducted as batch processes, bio-dried sludge 74 was recirculated in a study by Navaee-Ardeh et al. [9]. The effect of OCs was investigated by 75 Yang et al. using different concentration of glucose and ground food waste that were mixed 76 with bio-dried sludge for inoculation [10]. In addition to the AFR and bulking agent ratio, the 77 78 type of bulking agent, such as sawdust, wood pellets, straw, and corncob [11–13] and initial 79 moisture content for sewage sludge bio-drying [11], and inoculation ratio [13] have also been studied. 80

In the bio-drying process, moisture is removed by the combined actions of aeration 81 and biodegradation. Generated metabolic heat increases the temperature inside the reactor, 82 and this facilitates the moisture evaporation from the waste. Air then carries the evaporated 83 84 vapor and discharges it to the atmosphere. Measuring the weight of the waste before and after the experiment is the most common method of determining changes in moisture content. 85 However, this only shows the change in the water amount. To estimate certain ongoing 86 phenomena during the process, temperature, relative humidity in the airflow, and CO₂ 87 concentrations must be continuously measured, and metabolic water generation should be 88 taken into account. Among the previous studies, such continuous monitoring was performed 89

by Cai et al., Huiliñir and Villegas and Navaee-Ardeh et al. [6, 9, 14]. However, Cai et al. and
Huiliñir and Villegas estimated the metabolic water generation through the measurement of
VS changes by periodic waste sampling, whereas Navaee-Ardeh et al. estimated metabolic
water generation by changes in the CO₂ concentration, but only the AFR was changed as an
experimental condition.

95 Compared with the previously conducted studies that we reviewed, the novelty of our approach is characterized by the monitoring of the simultaneous effects of OC and AFR to 96 balance moisture, including metabolic water generation determined by continuous 97 measurement of the airflow. To establish the moisture balance, inlet and outlet flow of 98 moisture were estimated by continuous measurement of temperature and relative humidity of 99 the air. CO₂ concentrations in the outlet air were periodically analyzed to observe aerobic 100 biodegradation as well as metabolic water generation. Furthermore, contributions from the 101 AFR and temperature increase on water removal were quantitatively compared. 102

103

104 Materials and methods

105 Experimental equipment

106

107 Fig. 1 Schematic view of the reactor used in the bio-drying experiment

108

As shown in Fig. 1, the reactor used in this study was a 25 L acrylic cylindrical reactor with a diameter of 20 cm and a height of 70 cm. The reactor was filled with simulated wastes on a perforated base plate to ensure uniform air distribution from 30 to 60 cm in the reactor. The upper portion was covered with an acrylic lid with a hole for air exhaust. The reactor was insulated with a 5 cm thick layer of Styrofoam. A blower was connected to the bottom of the reactor with Teflon tubing. Ambient air was introduced via the blower and
moved upward through the reactor toward the exhaust port in the lid. Heat loss through
reactor wall by conduction and radiation is negligible because the loss is less than 1 % of
energy consumption for evaporation and temperature increase of air and solid materials in
lab-scale bio-drying reactor insulated with 100-mm of a hollow cotton wall [15].

The experiments were conducted from March to May 2015 and July to August 2016. All the experiments were conducted in a temperature-controlled room at 30 °C \pm 1 °C. The reactor was placed on an electronic scale (FG-60KBM-H, AND, Korea), and the total weight was measured and manually recorded at 12 h intervals. Each experimental run was terminated when the temperature of outlet air reached that of the ambient air.

124 Measurement and analysis

The temperature and humidity of the inlet and outlet air were monitored by a 125 humidity-temperature meter (TES-1365, TES, Taiwan). Three temperature sensors were 126 127 installed (two inside the reactor and the one at the outlet port in the lid) and connected to a thermometer (TES-1384, TES, Taiwan). The data logging interval was set to 4 min for 128 monitoring both ports. Inlet and outlet gas were sampled every 12 h to quantify CO₂ 129 concentrations by gas chromatography (GC-2014, Shimadzu, Japan). An in-line gas flow 130 meter (RMA, Dwyer, United States) was used to monitor the AFR. 131 At the end of all experimental runs, simulated waste was taken from the reactor, and 132

the final weight was measured. After weighing, the moisture content of the product was
determined by oven drying (forced convection drying oven, Chang Shin scientific co., Korea)
at 80 °C.

136 Experimental condition

137	In the experiment, commercial dog food (Prime Balance, Nutrena, Korea) was used to
138	represent easily biodegradable matter in the simulated waste. Nakasaki et al. and Chang et al.
139	reported that dry dog food can represent the easily biodegradable organic matter, and they
140	demonstrated good reproducibility, which resulted in uniform properties at the beginning and
141	end of the experiment [16, 17]. According to the nutrition level in the dog food used in this
142	experiment, it consisted primarily of carbohydrates (70% d.w.), crude protein (14% d.w.),
143	crude fat, crude fiber, and miscellaneous elements. Based on elemental compositions (C
144	44.7%, H 6.3%, N 2.4%, O 39.0%, ash 7.6% dry basis) determined by the authors, the
145	chemical composition of the VS was estimated to be C ₂₁ H ₃₆ O ₁₄ N.
146	OC was controlled by changing the ratio of dog food to wood pellets and included
147	10%, 25%, 50%, 75%, and 100%, by mass. Although the dog food is not 100%
148	biodegradable, its dry basis ratio is referred to as OC for the purpose of this study. The wood
149	pellets were assumed to be non-degradable during the bio-drying process due to their
150	relatively low biodegradability in the relatively short process time of the experiment [12]. As
151	a simulated waste, 3.1 kg of the dog food and wood pellet mixture with the previously
152	mentioned ratios was placed in the column reactor, and the initial moisture content was set at
153	40% by adding distilled water. Forty percent of the initial moisture content was determined
154	after measuring the field capacity of the dog food. With over 50% of moisture content, the
155	dog food easily becomes broken down. Return activated sludge, which was collected from a
156	commercial wastewater treatment facility, was injected to inoculate the simulated waste and
157	was equal to 10% of the dog food mass on a dry basis.
158	Regarding aeration, it has been suggested that the recommended aeration rates depend
159	on the substrate in the composting process [18]. The bio-drying process is a modified
160	composting process but focused more on water removal. Therefore, a slightly higher range of
161	AFR can be applied. In this study, the operation range applied in the past study, 0.4–1.1
162	L/min·kgVS, was used by referring to Adani et al. and Colomer-Mendoza et al. [7, 8]. When

163	the initial OC was 100%, 0.4 L/min·kgVS was multiplied by 3.1 kg, resulting in a value	of
164	1.2, which corresponded to approximately 1 L/min. Therefore, the AFRs selected for	
165	experimental analysis were set at 1, 2, and 3 L/min.	
166		
167	Table 1. Different variables and initial conditions in the experiments	
168	Table 1 summarizes the experimental conditions employed in this study. All the	
169	experimental runs were identified by the initial OC and AFR, such as "10-1" (i.e., 10% C	C
170	and a flowrate of 1 L/min). The average relative humidity (RH) of the inlet air in each	
171	experiment depended on the season. Table 1 presents the total days of operation, initial	
172	organic matter (dog food), and final organic matter and moisture content. The equations	
173	presented in next section were used to estimate final values.	
174		
175	Model	
176	Model equations	
177	The moisture balance in the reactor can be described by Eqs. (1) and (2).	
178	$\Delta w_{\text{nom}} (\text{kg/h}) = (V_{\text{out}} \times X_{\text{out}} \times 10^{-3}) - (V_{\text{in}} \times X_{\text{in}} \times 10^{-3}) $ (1)	
179	$\Delta w_{act} (kg/h) = \Delta w_{nom} - \Delta w_{gen} $ ⁽²⁾	
180	where V is AFR in m ³ /h, and X represents the water vapor content per unit volume of air	, in
181	g/m^3 . Eq. (1) is the water removal rate determined by the difference between moisture	
182	measured at the inlet and outlet of the airflow on a per hour basis, but it was nominal wit	10ut
183	considering the metabolic water generation (Δw_{gen}). Therefore, the actual water removal	rate,
184	Δw_{act} , was calculated using Eq. (2).	

Table 2 summarizes other equations used in the model, and the nomenclature is 188 provided at the end of this paper. The outlet AFR (Vout) was calculated by considering the 189 change in air density of the inlet airflow (Vin) (Eq. (3)). X, which denotes the water vapor 190 content per volume of air, was calculated using Eq. (4) as a function of water vapor pressure 191 (pv). The maximum value of water vapor pressure that can be reached at any temperature is 192 193 defined as the saturated water vapor pressure (pvs). The ratio between pv and pvs is the RH. For biodegradation, it was assumed that the organics were fully degraded which can 194 thus be expressed by Eq. (7). CO₂ generation rate (ΔC_{gen}) was estimated by the difference 195 between the CO₂ concentrations in the air at the inlet and outlet (Eq. (8)). Degraded organics 196 and generated metabolic water per unit time can be calculated using Eqs. (9) and (10), which 197 are based on Eq. (8). 198

The mass of organics (M₀) and moisture (W) at a particular time or its change during a particular period of time can be estimated by the integration of each rate (ΔM_0 , Δw). Moisture content (MC) can be calculated by the ratio between water mass to total waste mass at a specific time, and OC was estimated by the ratio of M₀ to total dry mass.

The rate of heat generation, ΔQ_{gen} , was calculated using Eq. (11) by multiplying the reaction heat of the degraded organics. Spoehr and Milner suggested the empirical method for calculating the heat of combustion for any type of organic matter is expressed by Eq. (12),

206
$$Q(kJ/kg) = \left(127 \times \frac{\{100 \times (2.66 \times C\% + 7.94 \times H\% - 0\%)\}}{398.9} + 400\right) \times \frac{4.184 \, kJ}{1 \, kcal}$$
(12)

where Q is the heat of combustion for degraded organics, and C%, H%, and O% are the weight percentages of carbon, hydrogen, and oxygen, respectively, on an ash-free basis [19]. For the dog food used in this study, its heat of combustion was estimated to be 20406 kJ/kg. Heat transfer in the inlet and outlet airflow (ΔQ_{in} and ΔQ_{out}) is calculated using the sum of dry air and water vapor enthalpy by applying Eq. (13).

212 Example of model output

Fig. 2 Experimental data and model output of run "50-3" (a) Temperature and CO₂

concentration profiles (Measured), (b) Rate of water mass changes in balance (Estimated), (c)

215 Heat profiles (Estimated)

216

As an example of model output, Fig. 2 shows the time profile for the run 50-3 (i.e., 50% of initial OC and a 3 L/min inlet AFR). The average inlet RH was 14.0% (see Table 1). Values in Fig. 2a were measured, and the others were calculated using the model in Table 2. During the initial period when biodegradation had not yet begun, which is referred to as "w/o BIO" in the figure, T_{in} and T_{out} were held constant, and the slight decrease of T_s was due to heat loss associated with evaporation.

After one day, CO₂ concentrations began to increase, which is indicative of a biodegradation process at work. The integrated area under the CO₂ curve presents the extent of organic degradation. During the biodegradation period, referred to as "w/ BIO," nominal water removal rate (Δw_{nom}) increased as T_{out} increased. This is one of the fundamental features of bio-drying, though actual water removal rate (Δw_{act}) was decreased by metabolic water generation rate (Δw_{gen}).

229 Microbial biodegradation of organic matter gradually decreased after it peaked at its 230 maximum. Either remaining OC or MC could have affected microbial activity, which is 231 discussed in detail later. Fig. 2c shows the heat balance. The difference between ΔQ_{gen} and 232 ΔQ_{out} was indicative of the heat used for evaporation or loss from the reactor.

233 **Reliability of model**

235	Fig. 3 Comparison of actual removed water mass (W_{act}) between experiment and model
236	during entire experimental period
237	
238	The mass of removed water (Wact) calculated by the model (integration of Δw_{act}) was
239	compared with that of the experiments during entire experimental period, as shown in Fig. 3,
240	where each label indicates the initial OC. The magnitude of error is generally within 20%.
241	Therefore, the model estimated the bio-drying phenomena reasonably well.
242	
243	Discussion
244	Drying mechanism in the bio-drying process
245	
246	Fig. 4 Temperature dependence of pvs and X_{sat} and increase of water vapor pressure (pv) in
247	bio-drying process
248	
249	Drying is a process of moisture transfer from the surface of waste to air. Evaporation
250	is driven by the differences of water vapor pressure between the surface of the waste and air.
251	The required heat for evaporation is obtained from the surroundings. Since the RH of the
252	outlet air was always 100% in all experimental runs, pv at inlet temperature increase to pvs at
253	outlet temperature. The driving force of evaporation can be expressed as the gap between two
254	points, i.e., outlet on the pvs curve and inlet in Fig. 4. As the temperature increased, the pvs
255	in the air increased so as X_{sat} .

The change of pv (water vapor pressure) in the air from the inlet to outlet is schematically shown by the broken arrow in Fig. 4. In w/o BIO period, before biological decomposition occurred, there were no increases in temperature due to the absence of heat associated with biodegradation. Consequently, the water vapor pressure pv in the air
increased only up to the pvs (saturated water vapor pressure) at the same temperature when it
was introduced into the reactor. However, once biodegradation proceeded under w/ BIO
period, the heat generation increased the waste temperature. Simultaneously, the initial
driving force of evaporation increased dramatically due to a high pvs, which was indicative
of an increase in the water content in the outlet air, X_{out}.

Water removal rate is increased with biodegradation as shown in Fig. 4, and the airflow carried saturated vapor out of the reactor. In w/o BIO period, only the influence of AFR can be discussed, and the relationship $1 - (^{RH}/_{100}) = (\Delta w_{act} = \Delta w_{nom} \text{ in this case})$ for different AFR by taking $1 - (^{RH}/_{100})$ as x-axis (Fig. 5). The higher the AFR, the more water was removed, and simultaneously, the lower the RH of the inlet air, which resulted from the large amount of water removal associated with the increasing gap between the pvs and the pv.

Fig. 5 Relations between water removal rate and RH of inlet air under different AFR during
w/o BIO period

274

In Fig. 5, a regression line for AFR = 1 L/min was first determined by assuming the removal rate was zero at an RH of inlet air = 100%, whereby the lines for AFR = 2 L/min and L/min are simply multiplied by 2 and 3, respectively. That is, AFR has simply the replacement effect of saturated air in the reactor.

279 Biodegradation of organic matter and its limitation

280

Fig. 6 CO₂ generation rate and moisture content profiles during entire experimental period (a)
AFR 1 L/min, (b) AFR 3 L/min

284	Different initial conditions of the OC and AFR induced different biodegradation
285	characteristics. To observe the extent of biodegradation, the CO ₂ generation rate (ΔC_{gen}) and
286	MC profiles are shown in Fig. 6. The $\triangle C_{gen}$, expressed in kmol/h, is calculated using the
287	AFR and CO ₂ concentrations in the outlet air (Eq. (8)). The integration of each curve is
288	proportional to the amount of degraded OC. The numbers in parenthesis indicate the initial
289	and final OC, which are defined by the ratio of organics to total dry solids.
290	CO ₂ generation rate curves of all runs were bell-shaped and had longer tails at lower
291	AFRs and higher OC values. In runs with the AFR set at 3 L/min (Fig. 6b), biodegradation
292	did not continue very long compared to the runs with lower AFRs because microbial activity
293	was limited by low levels of MC, even though sufficient OC was still available (i.e., 19%,
294	42%, and 83% corresponding to initial OC values of 25%, 50%, and 100%, respectively).
295	The low MC was caused by high AFR values that rapidly carried out all vaporized water.
296	By contrast, in runs using an AFR of 1 L/min, biodegradation continued for a longer
297	period of time until the OC decreased to 12% and 27%, corresponding to initial OC values of
298	25% and 50%, respectively. During the experiment, MC was maintained around 40% due to
299	the low AFR. In this case, biodegradation was terminated due to the low concentrations of
300	organics, not by moisture. In run 100-1, biological degradation ceased in spite of 67% of the
301	organics remaining because the feed material was composed only of dog food. Without
302	bulking material (i.e., wood pellets), the dog food stuck together, and the biodegradation was
303	limited due to a reduction in the contact area associated with short-circuiting of the airflow
304	around larger masses of dog food.

- 305 Effects of air flow and biodegradation
- 306

Fig. 7 Conceptual diagram of water removal rate in the bio-drying process

309	Fig. 7 depicts a conceptual diagram of the water removal rate in the bio-drying
310	process. Metabolic water generation rate (Δw_{gen}) is depicted as a negative value to indicate
311	added water by bio-drying process, and the water removal rate during the w/o BIO period is
312	denoted as Δw_{air} . From this figure, the following three water removal rates during the w/ BIO
313	period can be defined.
314	Effect of airflow: Δw_{air}
315	Effect of temperature increase (nominal): Δw_{nom} - Δw_{air}
316	Effect of temperature increase (actual): Δw_{nom} - Δw_{air} - Δw_{gen}
317	Given that the time profile was different among experiments (refer to Fig. 6), a
318	comparison of the water removal rate and maximum temperature of the simulated waste at
319	the peak point of CO ₂ concentration for all the runs is shown in Fig. 8.
320	
321	Fig. 8 Water removal rate defined in Fig. 7 at the peak point of CO ₂ concentration (a) AFR 1
322	L/min, (b) AFR 3 L/min
323	
324	Except for the runs with 10% of the initial amount of OC, where less heat generation
325	occurred due to the small amount of organic matter, the maximum temperature of the outlet
326	air ranged between 45 °C and 50 °C. The metabolic water generation rate, Δw_{gen} , remained
327	virtually constant regardless of AFR and initial OC. A constant Δw_{gen} indicates that
328	biodegradation rate at peak time did not depend on the experimental conditions in this study.
329	Compared with the Fig. 8a and Fig. 8b, the nominal effect of temperature increase
330	$(\Delta w_{nom}-\Delta w_{air})$ on water removal remarkably increased as the AFR increased, but so did
331	Δw_{air} . Airflow replace the saturated vapor as mentioned in previous section, so replaced
332	volume of air is proportionately increased with AFR in unit time. To exclude the increased

effect of replaced air, each water removal rate was divided by the AFR, $(\Delta w_{nom}-\Delta w_{air}) / V$ and $\Delta w_{air} / V$, as shown by the broken line in Fig. 8b, and these were similar to the result when the AFR was 1 L/min. Therefore, the effect of airflow was higher than the temperature increase.

As a result, the actual water removal rate, which was determined by the difference between $(\Delta w_{nom} - \Delta w_{air})$ and Δw_{gen} curves also increased with AFR because Δw_{gen} remained virtually constant regardless of the AFR.

340 Total water removal during w/ BIO period

The previous section discussed the water removal rate at the peak point of CO₂ concentration. However, the efficiency of drying should be evaluated by the total amount of removed water throughout the experiment period. In Fig. 9, the integrated amount of water removal during the w/ BIO period is shown.

345

Fig. 9 Removed water mass during w/ BIO period (a) Comparison of nominal removed water
mass (W_{nom}) and actual removed water mass (W_{act}), (b) Effect of temperature increase
(W_{nom}-W_{air}, W_{nom}-W_{air}-W_{gen}) on water removal compared with the effect of airflow (W_{air})

As shown in Fig. 9a, the amount of nominal removed water mass, W_{nom} , increased as the initial OC increased. This was caused by the difference in the duration of aerobic biodegradation. In other words, as shown in Fig. 6a, when the initial OC is high, the aerobic reaction continued for a longer period of time. Therefore, the amount of moisture removal increased with a higher water vapor pressure (pvs) and with a longer duration of saturated vapor replaced by airflow.

There was little difference by AFR in W_{nom} (Fig. 9a), because the shorter duration of the aerobic reaction associated with high AFR was made up or vice versa (see Fig. 6). The

duration of active biodegradation is shown in Fig. 9a. On the other hand, W_{act} significantly

decreased in lower AFR runs because of the considerable amount of metabolic water

360 generation by long biodegradation. Meanwhile, aerobic biodegradation was terminated due to

low MC (see Fig. 6b) which resulted from the significant replacement of moisture by a high

362 AFR.

Finally, the effect of temperature increase compared with the effect of AFR on water removal is presented in Fig. 9b. $(W_{nom}-W_{air})$ refers to the water mass removed by increases in temperature and $(W_{nom}-W_{air}-W_{gen})$ shows the ultimate amount of water removed, including the negative effect of added metabolic water. All points were plotted against W_{air} , which is the water removal solely associated with aeration. OC values of 10%, 50%, and 100% are plotted for comparison among all runs, and each OC is represented with different marks.

In each AFR condition, the higher the initial OC, both Wair and (Wnom-Wair) increased 369 due to the longer period of elapsed time, which maximizes the effect of increases in 370 temperature. However, when metabolic water is taken into account, the actual water removal 371 (W_{nom}-W_{air}-W_{gen}) by biodegradation decreased at lower AFR values, which was especially 372 373 true in runs 10-1 and 50-1 that showed negative values or values close to zero due to the reduced replacement effect. In case 100-1, agglomerated feed materials interrupted the air 374 passage, and this resulted in less biodegradation as well as less metabolic water generation. 375 When comparing the x- and y-axis values of (W_{nom}-W_{air}-W_{gen}), which are equal to the actual 376 water removal, the effects of temperature increase associated with biodegradation on water 377 removal were always lower than those associated with air replacement. 378

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380 Conclusion
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381

Fig. 10 Overall water removal mechanism in the bio-drying process

384	Fig. 10 summarizes the overall water removal mechanism in the bio-drying process
385	under different initial conditions, including variations in OC (organic content), AFR (airflow
386	rate), and RH (relative humidity) of the inlet air. Evaporation is driven by the difference
387	between the pvs (saturated water vapor pressure) of the waste surface and the pv (water vapor
388	pressure) in the passing air, and this driving force increased either due to temperature
389	increases associated with biodegradation or the dryness of introducing air. However, high OC
390	was a negative contribution with respect to water removal due to the generation of metabolic
391	water. On the other hand, saturated vapor in the reactor was carried out by airflow, so high
392	AFR enhanced the water removal rate. Water removal associated with air replacement was
393	generally greater than that associated with temperature increases caused by biodegradation.
394	But excessive AFR would terminate biodegradation due to the reduction in MC even though
395	organics remained.

In the bio-drying process, all the parameters are interdependent, and there are several feedback loops as previously mentioned. The findings of this study can be used for the design and operation of a full-scale system.

Appendix

Nomenclature			
Symbol		Unit	Definition
	t	days	Time
	Т	°C	Temperature
	V	m ³ /h	Airflow rate
	CO ₂	%	CO ₂ concentration
State variables	Х	g/m ³	Water vapor per unit air volume
	RH	%	Relative humidity
	ρ_a	kg/m ³	Density of dry air
	pv	Pa	Water vapor pressure
	pvs	Pa	Saturated water vapor pressure
	Мо	kg	Organic mass
Decomposition	ΔΜο	kg/h	Organic degradation rate
Decomposition	ΔC_{gen}	kmol/h	CO ₂ generation rate
	OC	%	Organic content
	W	kg	Water mass
Maisture	Δw	kg/h	Water removal rate
WOISture	Δw_{gen}	kg/h	Metabolic water generation rate
	MC	%	Moisture content
	ΔQ	kJ/h	Heat flow rate
	ΔQ_{gen}	kJ/h	Metabolic heat generation rate
Heat	Q	kJ/kg	Heat of combustion for degraded organics
	h _{dry}	kJ/kg	Enthalpy of dry air
	h_{vapor}	kJ/kg	Enthalpy of water vapor

Subscript	Definition
in	Inlet
out	Outlet
S	Waste
nom	Nominal

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Figure captions:

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Fig. 3 Comparison of actual removed water mass (W_{act}) between experiment and model during entire experimental period

Fig. 4 Temperature dependence of pvs and X_{sat} and increase of water vapor pressure (pv) in bio-drying process

Fig. 5 Relations between water removal rate and RH of inlet air under different AFR during w/o BIO period

Fig. 6 CO₂ generation rate and moisture content profiles during entire experimental period (a) AFR 1 L/min, (b) AFR 3 L/min

Fig. 7 Conceptual diagram of water removal rate in the bio-drying process

Fig. 8 Water removal rate defined in Fig. 7 at the peak point of CO₂ concentration (a) AFR 1 L/min, (b) AFR 3 L/min

Fig. 9 Removed water mass during w/ BIO period (a) Comparison of nominal removed water mass (W_{nom}) and actual removed water mass (W_{act}), (b) Effect of temperature increase (W_{nom}-W_{air}, W_{nom}-W_{air}-W_{gen}) on water removal compared with the effect of airflow (W_{air})

Fig. 10 Overall water removal mechanism in the bio-drying process

Experimental condition									
	Initial				Initial	Initial Final			
D	OC	V	RH ± SD	Time	Mo	Mo	W		
Runs	%	L/min	%	days	kg	kg	kg		
10-1	10	1	61.1 ± 4.7	19	0.314	0.000	1.842		
25-1	25	1	23.8 ± 5.0	16	0.786	0.375	1.404		
50-1	50	1	23.8 ± 5.5	16	1.571	0.879	1.420		
75-1	75	1	15.0 ± 7.2	32	2.357	1.475	0.919		
100-1	100	1	33.9 ± 6.1	26	3.143	2.181	1.070		
10-2	10	2	59.4 ± 3.2	12	0.314	0.053	1.603		
25-2	25	2	15.4 ± 5.3	10	0.786	0.484	1.090		
50-2	50	2	23.3 ± 5.1	14	1.571	1.094	0.817		
75-2	75	2	10.1 ± 1.7	14	2.357	1.815	0.719		
100-2	100	2	36.3 ± 6.8	16	3.143	2.639	0.629		
10-3	10	3	59.4 ± 3.2	11	0.314	0.062	1.303		
25-3	25	3	16.9 ± 5.4	7	0.786	0.612	0.996		
50-3	50	3	14.0 ± 4.7	8	1.571	1.318	0.884		
75-3	75	3	9.9 ± 1.9	10	2.357	2.003	0.579		
100-3	100	3	33.6 ± 6.7	13	3.143	2.644	0.350		

Table 1. Different variables and initial conditions in the experiments

Contents	Equation	
Airflow rate of outlet air (m ³ /h)	$V_{out} = \frac{(273.15 + T_{out})}{(273.15 + T_{in})} \times V_{in}$	(3)
Water vapor per unit air volume (g/m ³)	$X = \frac{217 \times pv}{273.15 + T}$	(4)
Water vapor pressure (Pa)	$pv = RH \times pvs$	(5)
Saturated water vapor pressure (Pa)	$pvs = 6.1078 \times 10^{\frac{7.5 \times T}{T + 237.3}}$	(6)
Organic degradation	$C_{21}H_{36}O_{14}N + 22.3 O_2 \rightarrow 21 CO_2 + 16.3 H_2O + NH_3 + Heat$	(7)
Generated CO ₂ (kmol/h)	$\Delta C_{gen} = [(V \times CO_2)_{out} - (V \times CO_2)_{in}] \times \frac{1}{100} \times \frac{1 kmol CO_2}{22.4 m^3}$	(8)
Degraded organics (kg/h)	$\Delta M_{O} = \frac{1}{21} \times \Delta C_{gen} \times \frac{533.2 \ kg}{1 \ kmol}$	(9)
Metabolic water (kg/h)	$\Delta w_{gen} = \frac{16.3}{21} \times \Delta C_{gen} \times \frac{18 kg}{1 kmol}$	(10)
Heat generation (kJ/h)	$\Delta Q_{gen} = \Delta M_0 \times 20406 \ kJ/kg$	(11)
Heat transfer in air flow (kJ/h)	$\Delta \mathbf{Q} = h_{dry} \times \rho_a \times V + h_{vapor} \times X \times 10^{-3} \times V$	(13)
Enthalpy of dry air (kJ/kg)	$h_{dry} = 1.006 \times T$	(14)
Enthalpy of water vapor (kJ/kg)	$h_{vapor} = 1.805 \times T + 2501$	(15)
Density of dry air (kg/m ³)	$\rho_a = 1.293 \ \times \ \frac{273.15}{273.15 + T}$	(16)



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