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Design and operation of the bio-toilet system

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Abstract

Criteria for the proper design and operation of the bio-toilet have been established neither by the manufacturers nor by the authorities. Based on results of experimental research already reported by us, criteria for the proper design and operation of the bio-toilet system were established. In addition, size of the composting reactor was determined attending such criteria and based on results of drying tests conducted in a laboratory-scale drying device designed by us. Design procedure considered the daily water loading, due to contributions of urine and feces, as the main criterion. Organic loading, in terms of feces/sawdust ratio (F/S) resulted to be a non-governing factor for the design, because it was very low. Even though mixing frequency may enhance the biodegradation and drying rates in the composting reactor, the design was conducted regarding no mixing conditions due to evaluation of its effect on such rates has not been studied yet. However, mixing frequency was considered an important factor for operating the system. Establishment of operation criteria led to the formulation of a operation scheme where three main zones are distinguished: i) “green zone” where the best composting performance is expected; ii) “yellow zone” where biodegradation can be conducted but performance is not the most efficient; iii) other zones where operation of the bio-toilet is not recommended because odor problems and human health risk will develop, or in the worst case, biodegradation of feces will not occur.

1. Introduction

The bio-toilet is a thermophilic composting toilet that is becoming commercially available and it is actually used in Japan in public parks, sightseeing areas, and households (Fig. 1). However, criteria for the proper design and operation have been established neither by the manufacturers nor by the authorities. Users and owners of this toilet system just follow the recommendations, stated in most cases verbally, of manufacturers and providers to operate it. These recommendations are given based on their experiences in operating such systems, rather than supported in scientific and technical arguments. Bio-toilet systems are sold to consumers as units already manufactured in which user or planners do not have any participation in the design process. Thus, the necessity or duty of having proper design criteria mainly resides in manufacturers. Operation, on the other hand, involves manufacturers but also providers, users and planners.

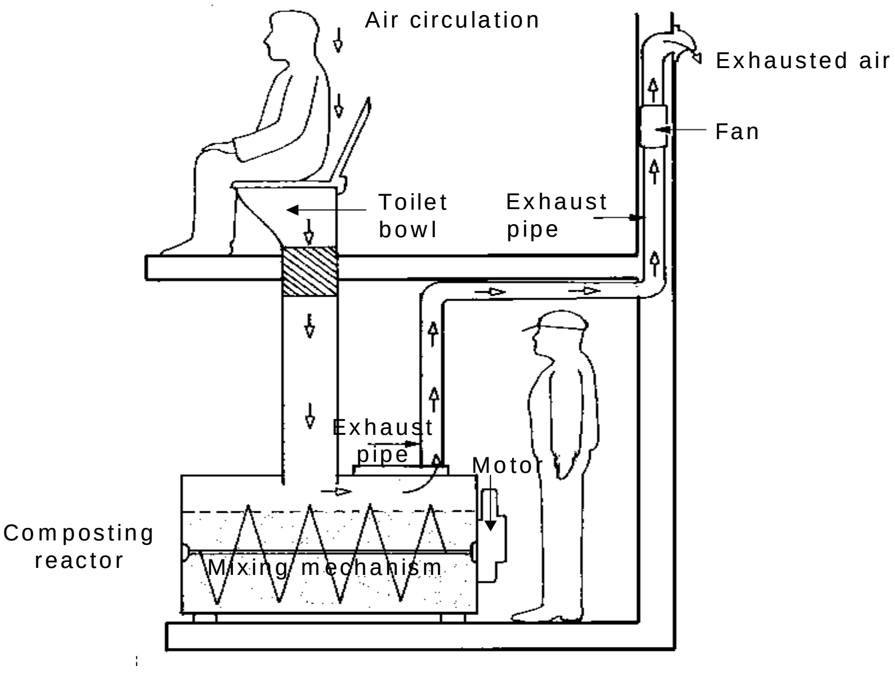

Fig. 1. The bio-toilet system and its components.

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Proper design of the bio-toilet implies that the system fulfills criteria such as: safety, functionality, economy, esthetics, and social and environmental affordability. Attending the criteria of functionality and social and environmental affordability, the bio-toilet must be designed with the aim of accelerating decomposition of human excreta, optimizing efficiency, and minimizing any potential environmental or nuisance problems (odor). These objectives must couple safety, low manufacturing and operational costs, and esthetics to become an affordable option for the users. Thus, design process of the bio-toilet will consist in determining the size of the composting reactor that ensures the achievement of the criteria mentioned previously.

Based on the results achieved in the previous studies, establishment of criteria for the proper design and operation is the aim of this paper. Because bio-toilet deals with the evaporation of the water contained in human excreta, theory and concepts of drying of solids are introduced. In addition, results of drying tests, conducted in a laboratory-scale drying device designed by us, are discussed and used in the design process.

2. Considerations for the operation

As mentioned above, the bio-toilet system is managed with the aim of accelerating decomposition, optimizing efficiency, and minimizing any potential environmental or nuisance problems (odor). The conditions under which the composting reactor must be operated to meet these goals are given by the results of the research presented in previous papers, especially related to moisture content and temperature. Thus, criteria for the proper operation of the system under the current configuration are summarized as follows:

a) Continuous thermophilic aerobic conditions and organic loading are not limiting factors for the composting process in the bio-toilet system. However, constrains associated with high moisture contents may affect the performance of the composting process if organic loads beyond the feces-sawdust ratio (F/S) equal to 25% are planned to be used (Lopez Zavala et al., 2005).

b) Optimum moisture control and management in the composting reactor of the bio-toilet system should take into account not only high performance on biodegradation of feces, but also problems of odor and anaerobic emissions, and necessities of maintenance and services, associated with frequency of sawdust replacement. These requirements could be achieved by keeping moisture contents at 60% or little higher, but avoiding levels higher than 65%, i.e., moisture levels near, but lower than the critical moisture. Very low moisture contents, less than 50%, should also be avoided to ensure proper environment for microorganisms and consequently faster and complete stabilization of organic matter contained in feces (Lopez Zavala et al.2004a).

c) Composting in the bio-toilet system is characterized by different biological response of microorganisms depending on the moisture content under which the process is conducted. Low moisture contents (< 65%) ensured aerobic degradation of feces, whereas high moisture levels ($\geq 65\%$) caused both aerobic and anaerobic decomposition. Because anaerobic conditions occurred at high moisture contents ($\geq 65\%$), microorganisms' activity generated odor and VFA emissions. In addition, simultaneous aerobic and anaerobic processes at high moisture levels caused the increase of sulfate concentrations and formation of nitrites in the sawdust matrix, even though the composting process was conducted at thermophilic temperatures. At low moisture contents, anaerobic emissions, nitrification products and increase of sulfate concentrations were not detected (Lopez Zavala et al.2004a).

d) Critical moisture was the frontier moisture content which defined either the highest degradation rates or the beginning of odor and anaerobic emissions, increases of sulfate concentrations, and the nitrification process under thermophilic conditions. Thus, critical moisture may be adopted as a simple physical operation parameter and it was found to be approximately 65% (Lopez Zavala et al.2004a).

e) Mesophilic and thermophilic microorganisms showed different response to the temperature; additionally, results suggest that the optimum temperature from the viewpoint of feces biodegradability is within the thermophilic range, nearly to 60°C. At 70°C the activity of biomass was very low. It was clear that enzymatic activity of microorganisms diminished remarkable at this high temperature. At temperatures lower than 60°C, biodegradation rates of feces slowed following a pattern described by Arrhenius equation. In the mesophilic range, hydrolyzability of organic matter was remarkably dependent of the temperature at which the composting process was conducted (Lopez Zavala et al.2004b).

f) Temperatures over than 45°C (thermophilic range) were more effective for inhibiting the coliforms colony-formation and bacteriophages plaque-formation, consequently for pathogens inactivation. Coliform bacteria colony formation at 60°C was inhibited in only 1.17 h, whereas at 50 and 45°C the inactivation occurred after 8 and 24 hours, respectively. On the other hand, at temperatures lower than 45°C, it took much longer time to obtain 6-log reduction of CFU. The decay process of bacteriophage also showed the same profile. Temperature distribution in the bio-toilet system was not uniform, even just after mixing the sawdust matrix. The non-uniformity in temperature distribution caused reduction of effectiveness for inhibiting pathogens. Results of risk assessment showed that the reduction of compost withdrawal infection risk to an acceptable level ($1x10^{-4}$ per year) is achieved *i)* by mixing the sawdust mixing 20 times per day during 2 days or *ii)* by mixing 15 times per day during 3 days after the last using-event of the bio-toilet in current operating bio-toilet. Eliminating low temperature zone was more effective to reduce reaction time to obtain affordable infection risk especially in low mixing frequency such as 2 times per day than increasing high temperature volume (Nakata et al., 2004).

g) Low pH (6-7) should be kept in the composting reactor of the bio-toilet system to ameliorate the high nitrogen losses observed. During feces degradation conducted at 55°C, T-N losses in the form of NH_3 were on the order of 94%, regardless of the organic loading. Experiments with urine confirmed that ammonification of organic nitrogen occurred in the composting reactors at high and low temperatures. At 40 and 60°C, lower T-N reductions were observed, but the ammonia releases from the composting reactors were approximately 97.5% of T-N reductions. Unlike, at 20 and 30°C, T-N reductions were approximately 81.5% and 89.1%, respectively, whereas ammonia losses resulted to be about 57% of T-N reductions (Lopez Zavala et al., 2004c).

h) Nitrification products were not detected in all range of temperatures evaluated, except when high moisture content were kept ($\geq 65\%$). High salinity, especially high concentrations of Cl, seemed to be the main inhibitory factor for the nitrification process in the composting reactor. Therefore, alternative methods to conserve nitrogen in the sawdust matrix, for instance, mineralization of NH_4 in the form of struvite crystals, were suggested to enhance the agricultural quality of the compost generated, and to reduce the human health risk and air pollution problems due to ammonia emissions (Lopez Zavala et al., 2004c).

In the practice, above optimum temperature and moisture conditions in the composting reactor can be achieved by *i)* monitoring continuously the composting process; *ii)* manipulating the temperature controller of the system, the mixing frequency, and the water amount for cleaning purposes. pH control is more difficult to achieve, but the addition of sulfates containing for instance magnesium may help to reduce pH or enhance the formation of struvite crystals at higher pH.

Based on above considerations, an operation scheme for the bio-toilet was prepared (Fig. 2). In this scheme, three parameters were considered, temperature, moisture content, and mixing frequency. The effect of mixing frequency on human health risk was studied by Nakata et al. (2004); however, the effect on moisture content reduction due to drying process and on biodegradation rates has not been studied yet; therefore, the operation zones associated with mixing frequency are not conclusive, so that they are delimited by dashed lines. The white doted zone (green zone) denotes the conditions where the best performance of the bio-toilet is expected. In the shadow-doted zone (yellow zone) the composting process can be conducted, but performance is not the most efficient. Out of these two zones operation of the bio-toilet is not recommended because odor problems and human health risk will come, high operation cost for concept of excessive mixing, or in the worst case, biodegradation of feces will not occur because microorganisms will die due to adverse environmental conditions.

3. Considerations for the design

Under the current configuration of the bio-toilet system (Fig. 1), the size of the composting reactor is determined by conditions such as:

a) Water loading rate due to daily contributions of urine, water contained in feces, and water for cleaning the toilet bowl.

b) Drying rate, i.e., evaporation rate of water contained in urine and feces and cleaning water.

c) Organic loading rate due to daily feeding of feces and toilet paper; i.e., feces-sawdust ratio (F/S).

d) Biodegradability and biodegradation rate of toilet wastes which are affected by several factors, among them the environmental conditions such temperature, moisture content, pH, oxygen availability, etc.

e) Mixing frequency.

The water loading and drying rates affect water balance in the bio-toilet system. Lopez Zavala et al.(2004a) established that moisture content in the sawdust matrix should be set less than 65% and nearly to 60% for optimum biodegradation performance. Thus, design of the composting reactor must be conducted regarding that the moisture content in the sawdust matrix should be kept at that level.

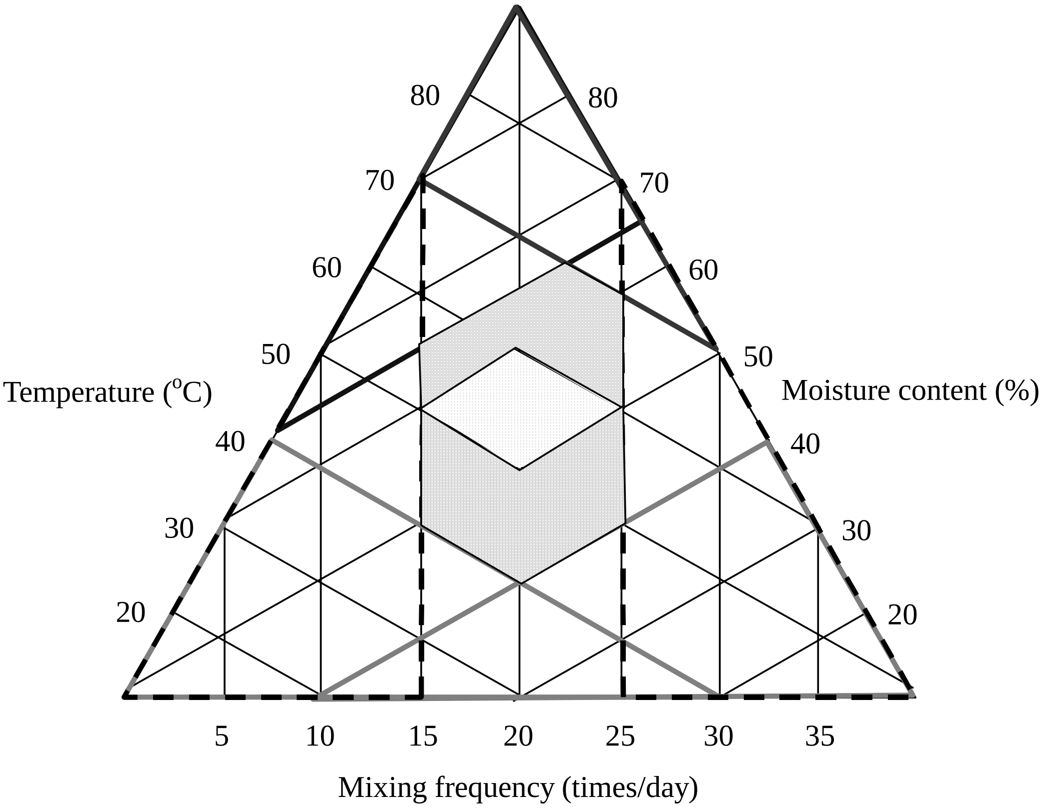

Fig. 2. Criteria for proper operation of the bio-toilet system.

The average daily feces and urine production rates per capita per day found in the literature are approximately 130 g (wet basis) for feces and 1200 ml for urine (Almeida et al., 1999; Del Porto and Steinfeld, 2000). The water content of feces is approximately 82% (Lopez Zavala et al., 2002). Thus, the daily water-loading rate of human excreta totalized 1307 ml per capita per day (or 1325 g per capita per day, if density of urine is 1.015 g/cm^3). Because no studies have been conducted to evaluate the amount of water needed for cleaning the bio-toilet, but regarding that the quantity used for that purpose is relatively small, cleaning water may be considered negligible for design purposes. On the other hand, the design of the composting reactor must ensure the evaporation of the water loaded in one day, in such way the bio-toilet is able of receiving the next day water loading. If water content of feces is 82%, the daily organic loading in dry basis due to feces is 23.5 g per capita per day. Compared with water-loading rate, organic loading rate is very low. Therefore, as mentioned previously, the size of the composting reactor will be mainly determined by the water-loading rate.

Thermophilic conditions in the composting reactor of the bio-toilet system are provided in order to kill pathogens, accelerate decomposition, and enhance drying process. Temperatures between 50 and 60°C resulted to be very effective for pathogens inactivation (Nakata et al., 2004). In addition, evaluation results of temperature effect on aerobic biodegradation of feces (Lopez Zavala et al., 2004b) suggest that the optimum temperature from the viewpoint of feces biodegradability is within the thermophilic range, nearly to 60°C. Therefore, the design of the system must be conducted regarding that the system will be operated at that temperature.

Lopez Zavala et al. (2005) established that organic loading does not constitute a limiting factor for biodegradation of feces using sawdust as matrix for F/S ratios less than 25%. However, moisture content of feces limits the operation of the composting reactor under high organic loadings. Consequently, the size of the composting reactor may be determined first by regarding the water balance as a criterion and then the organic loading (F/S ratio) is revised.

Characterization of feces based on mass units is and affordable way to evaluate the quantity and composition of the residue accumulated in the composting reactor that interferes in the design and operation of the bio-toilet system (Lopez Zavala et al., 2002). Further more, 44% of TS of feces will remain in the composting reactor after biodegradation. These solids will accumulate during the time operation of the system and their volume should also be considered during the design process. Thus, the size of the composting reactor should be also revised during the design process to consider the accumulation of biological inert material.

On the other hand, even though toilet paper is biodegradable organic material, its decomposition is quite slow compared with feces biodegradation because toilet paper is a cellulosic material that is degraded by actinomycetes and/or fungi, microorganisms that are not dominant in the composting reactor of the bio-toilet system. Therefore, for design purposes toilet paper may be considered as a part of the bulking matrix (sawdust).

Mixing in the bio-toilet enhances the incorporation of toilet wastes and air into the sawdust matrix, and the homogenization of the sawdust matrix in terms of organic matter, microorganisms, water content and temperature distribution. Thus, the direct benefits of mixing are: acceleration of toilet wastes decomposition, increase of drying rates that will lead to smaller size of the composting reactor, enhancement of pathogens inactivation, and reduction of odors and possible anaerobic emissions. In general mixing will improve the performance of the bio-toilet system. Nakata et al. (2004) evaluated the mixing frequency effect on reduction of health risk when compost is withdrawn from the composting reactor. However, evaluation of mixing frequency on drying rates has not conducted yet, therefore, for design purposes mixing may be considered as a “safety factor”. Thus, the size of composting reactor may be estimated regarding no mixing conditions.

4. Materials and methods

The design of the composting reactor must ensure the evaporation of the water loaded in one day, in such a way the bio-toilet is able of receiving the next day water loading. In general, drying of sawdust matrix means the removal of water contained in human excreta and that used for cleaning from the composting reactor, to lead the moisture content to an acceptably value, between 60 and 64%, as mentioned above. Thus, the composting reactor of the bio-toilet is acting as a “special dryer” whose size must be determined.

In order to determine the size of the composting reactor, it is necessary to know the time which will be required to dry a substance from one moisture content to another under specified conditions. We shall also wish to estimate the influence that different drying conditions will have upon the time for drying. Because of the limiting knowledge of the drying process, in the practice the drying time is determined by using experimental drying curves which are based on experimental drying tests. Measurements of the rate of batch drying are relatively simple to make and provide much information not only for batch but also for continuous operation (Treybal, 1968).

4.1. Experimental device

Figure 3 shows the schematic representation of the experimental device where drying tests were conducted. Temperature and relative humidity of the air flow was set constant by means of an incubator which allows temperature and relative humidity control in the range of 20 to 80^{o}C and 20 to 90%, respectively. Air speed was control by an air fan with capacity to produce speeds of about 3 m/s. The dry process was conducted in an insulated stainless steel rectangular channel to which a circular stainless vessel containing the sawdust was attached. This vessel was immersed in another to allow the continuous water circulation during the drying process. The temperature of circulating water was set constant by a temperature controller, as shown in Fig. 3. The sawdust vessel or container was attached and detached from the drying channel by means of a very simple mechanism. The dimensions of the drying channel are 14 cm width and 10 cm high. The sawdust vessel is 10.83 cm diameter. All the air-circulating conduits were made of insulant material to avoid heat transfer. Air speed was measured with an anemometer installed at the end of the drying channel. Temperature and relative humidity of the air were also monitored continuously before and after the sawdust vessel by using special sensors. In addition a temperature sensor was set inside the sawdust vessel to monitor the temperature changes inside the sawdust matrix.

4.2. Drying tests

The air circulation in the bio-toilet system is shown in Fig.1. As seen, air entering the composting reactor comes from inside the house, consequently the temperature and relative humidity of such air are those exiting inside the toilet room. The recommended temperature and relative humidity inside the home are well known to be 23 to 25^{o}C and 50 to 65%, respectively. On the other hand, as established above, the composting reactor of the bio-toilet should be operated at a temperature nearly to 60^{o}C. Thus, two drying test were conducted regarding the conditions summarized in Table 1.

Temperature and relative moisture of air at the incubator, before and after the sawdust vessel, and temperature inside of it were monitored every 20 minutes. Changes of the sawdust moisture content were measured gravimetrically hourly. Drying tests were conducted until no more changes in moisture content were observed.

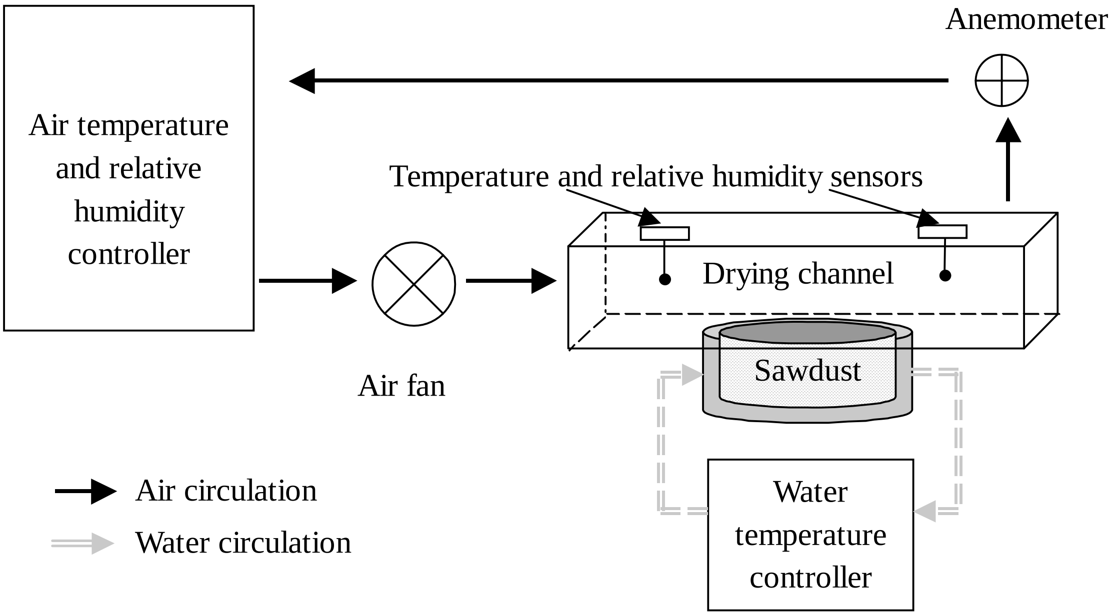

Fig. 3. Schematic representation of the drying experimental device.

Table 1. Drying tests conditions.

Test	Incubator		TCW	Air flow rate	MCS	MDS
	Temp. (^{o}C)	RH (%)	(^{o}C)	(m/s)	(%)	(g)
1	25	50	60	3.0	81.1	31.9
2	25	65	60	3.0	81.4	31.6

RH: Relative humidity; TWC: Temperature of circulating water in the sawdust vessel; MCS: moisture content of sawdust; MDS: mass of dried sawdust.

5. Results and discussion

5.1. Drying tests

Figure 4 shows the changes on moisture content of sawdust during drying tests. As seen, the differences in order of magnitude of the moisture content profiles at 50 and 65% relative humidity of air are not considerable; however, the moisture content of sawdust decrease faster at 50% relative humidity of air. In this figure, it is clear that approximately 24 hours were required to dry the sawdust.

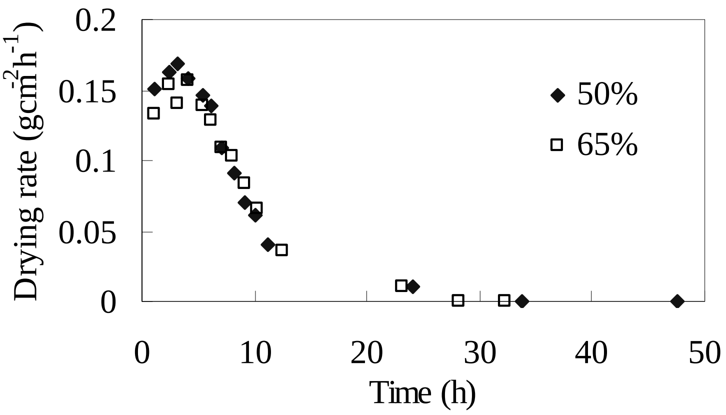

Fig. 4. Moisture content evolution during drying tests.

In Figure 5 the experimental drying rate profiles are shown. Like Fig. 4, no significant differences on drying rates were observed at 50 and 65% relative humidity of the air; however, drying rates were a little higher at 50% because the heat and mass transfer potential is higher a low relative humidity of the air. Two drying periods were observed, as described by the drying theory, the constant- and falling-rate periods, the average critical moisture was approximately 65% (or 1.85 g g^{-1} ds) and the corresponding drying rate was about 0.137 g cm^{-2} h^{-1}. As seen in the falling rate period, drying rate is almost linear to the moisture content. This result is important because eases the calculations during the design process due to operation of the composting reactor of the bio-toilet should be conducted in this drying period, nearly to 60% moisture content. The drying rate at this moisture content was approximately 0.123 g cm^{-2} h^{-1}.

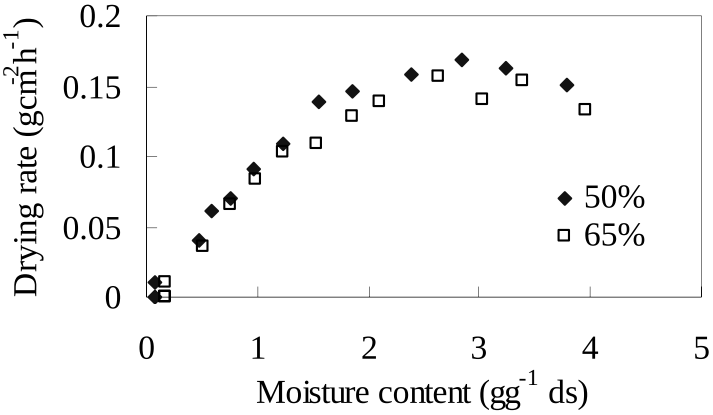

Fig. 5. Experimental drying rate profiles.

Fig. 6 depicts the temperature variation respect to the time inside the sawdust vessel. As seen, temperature was higher, nearly to 44°C, at the beginning of the drying tests, i.e., during the constant-rate period. Later, during the falling rate, the temperature decreased gradually until become almost constant (35°C) approximately 21 hours after the beginning of the experiment. Even though circulating water at 60°C heated the sawdust vessel, temperature of the sawdust matrix inside the vessel never reached that temperature. This was expected due to the heat transfer from the sawdust matrix to the air circulating at lower temperature inside the drying channel.

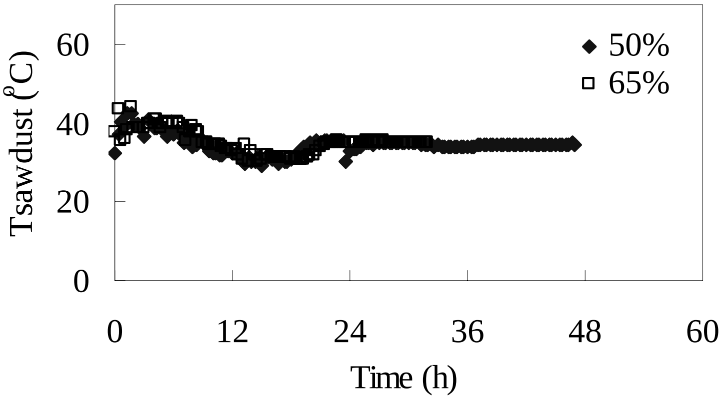

Fig. 6. Temperature evolution during drying tests.

5.2. Design of the composting reactor of the bio-toilet system

It was established above that the composting process in the bio-toilet should be conducted at 60°C and 60% moisture content for good performance. Based on these recommendations and regarding the results of the drying tests the size of the composting reactor may be determined as follows.

Estimation of the drying surface. From drying theory, the drying surface can be expressed as follows

$$A = \frac{M_S\left(W_1 - W_2\right)}{tDR_m} \quad \text{and} \quad DR_m = \frac{DR_1 - DR_2}{\ln\left(\frac{DR_1}{DR_2}\right)} \tag{1}$$

where A is the drying surface ; Ms is the mass of dry solids (sawdust plus feces); W_1 and W_2 water content changes from its initial value W_1 to its final value W_2;t is the time of drying; and DR_m is the logarithmic average of the drying rate DR_1, at water content W_1, and DR_2 at W_2

The water content is, by definition, the mass of water (Mw) divided by the mass of dry solids (Ms)

$$W = \frac{Mw}{Ms} \tag{2}$$

Thus, Eq. 1 can be transformed into

$$A = \frac{\left(Mw_1 - Mw_2\right)}{tDR_m} \tag{3}$$

where Mw_1 and Mw_2 are the water mass contributions of excreta at the beginning and end of the drying period. Thus,

Mw = Mass of urine + mass of water in feces + mass of water for cleaning

The moisture content in the composting reactor should not be lower than 50% to ensure proper environmental conditions for microorganisms responsible of feces degradation, as discussed above. Thus, moisture content of the sawdust matrix should change from 60 to 50% when drying occurs and from 50 to 60% due to contributions of water from human excreta. This 10% of moisture content variation must ensure the evaporation of total water contained in excreta.

It was established above that the daily water-loading rate of human excreta totalized 1307 ml per capita per day (or 1325 g per capita per day, if density of urine is 1.015 g/cm^3). On the other hand, it is easy to realize that the water loading to the composting reactor is not constant during the day; in other words, the water loading, due to excreta contribution, presents an hourly variation pattern. Therefore, the time interval where the water loading is critical (higher) must be identified and determined. Friedler et al. (1996) reported the domestic WC usage patterns for the U.K, for both weekdays and weekends. The weekdays' pattern is the most critical and is presented in Fig. 7. By using this pattern and based on the daily water loading rate (1325 g/capita/day), the hourly water-loading rate was estimated for one person and its plot is shown in Fig. 8.

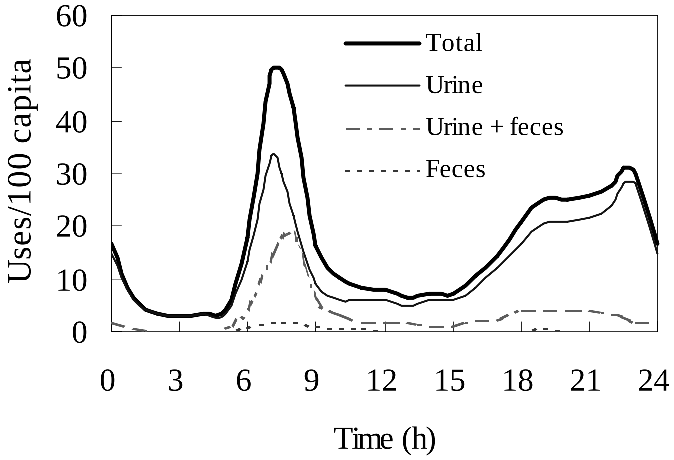

Fig. 7. U.K. domestic WC usage pattern for weekdays.

The critical water loading for a certain drying period during the day can be estimated from a cumulative water-loading plot by (Fig. 9). It was found from this figure that the critical water loading is approximately 208 g and occurs between the 6:00 and 9:00 hours. Thus, the difference ($Mw_1 - Mw_2$) and the drying time (t = 3 hours) of Eq. 3 are known. I the drying surface is estimated based on this critical conditions, the water content of the sawdust matrix will be in any time of the day within the required range, between 50 and 60%.

On the other hand, from Fig. 5 the drying rates at 60% (DR_1) and 50% (DR_2) moisture contents are

DR_1 = 0.132 g cm^{-2} h^{-1}

DR_2 = 0.087 g cm^{-2} h^{-1}

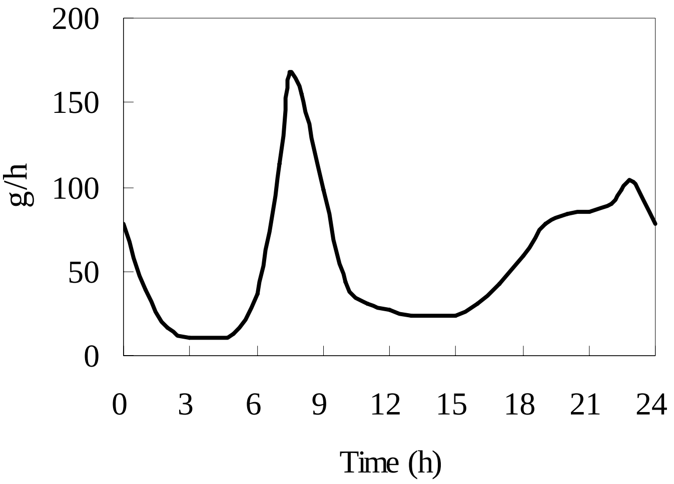

Fig. 8. Estimated hourly water-loading rate to the composting reactor due to human excreta.

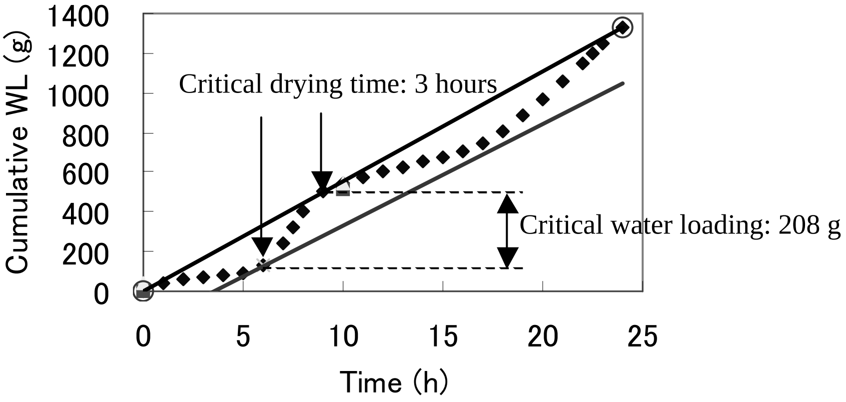

Fig. 9. Cumulative water loading (WL) to the composting reactor of the bio-toilet.

Substituting values, the logarithmic average *DRm* yields

$$DR_m = \frac{0.132 - 0.087}{\ln\left(\frac{0.132}{0.087}\right)} = 0.1079 \quad \text{g cm}^{-2}\ \text{h}^{-1}$$

Thus, the drying surface required to keeping the moisture content of sawdust matrix in the range 50 to 60% for the critical water loading and for one person yields

$$A = \frac{(208.0)}{3.0(0.1079)} = 643.0\ \text{cm}^2 \text{ per capita}$$

Estimation of the sawdust matrix volume. For design purposes, the volume of the sawdust matrix must ensure that *i)* moisture content becomes approximately 60% during the critical water loading to the system, and *ii)* critical water load is totally evaporated in the critical time (3 hours), i.e., moisture content of the sawdust matrix becomes approximately 50% after the critical drying period, approximately at 9:00 hours.

Rearranging the Eq. 2 and regarding that M_s is the mass of dry sawdust (M_{ds}) plus the mass of dry feces (M_{df}), yields

$$M_s = \frac{Mw}{W} = M_{ds} + M_{df}$$

Accordingly to Fig. 7, an hourly feces-loading pattern exists; however, the major contribution occurs within the critical water loading period too. Therefore, for design purposes it will be considered that all feces are loaded to the composting reactor in only one even and during the critical water loading period. The mass of dry feces generated per person per day was determined above as 23.5 g; therefore, the mass of dry sawdust required to have a water content (W) of 60% (or 1.5 g g^{-1}) is estimated as follows

$$M_{ds} = \frac{Mw}{W} - M_{df} = \frac{208}{1.5} - 23.5 = 115.0 \text{ g per capita}$$

Average density of the sawdust used in the bio-toilet under operation is about 0.19 g/cm^3 (Horisawa et al., 1999; Terazawa et al., 1995), therefore the volume of dry sawdust is

$$V = \frac{M_{ds}}{\delta_s} = \frac{115.0}{0.19} = 606.0 \text{ cm}^3 \text{ per capita (or 0.606 l per capita, approximately)}$$

The daily use of the bio-toilet causes the accumulation of biologically inert material in the composting reactor. This material occupies volume in the reactor that must be considered during the design process. Lopez Zavala et al. (2005) determined that 44% of solids remain in the composting reactor after degradation. Thus, the mass of solids that will accumulate in 6 months and in 1 year is

In six months:

$$Ms_{ac} = (M_{df})(0.44)(182.5 \text{ days}) = (23.5)(0.44)(182.5) = 1887.0 \text{ g per capita}$$

In one year:

$$Ms_{ac} = (M_{df})(0.44)(365 \text{ days}) = (23.5)(0.44)(365) = 3774.0 \text{ g per capita}$$

As seen, the cumulative mass of stabilized solids is much greater than the theoretical mass of sawdust required. Because the high porosity of the sawdust (78% approximately; Horisawa, 1999), the stabilized solids will fill up partially the pores of sawdust. When it happens, physical properties of the sawdust matrix such as density, porosity, air and water retention, and water storage capacity will also change affecting consequently the performance of the composting process. To avoid this, additional volume for remaining solids should be considered. Density of stabilized organic solids is unknown; however, studies of physical properties conducted on fine-texture mull soils report bulk densities of 0.74 g cm^{-3} (Wall and Heiskanen, 2003). Adopting this value as the density of the remaining solids in the composting reactor, the additional volume to be considered in the design is:

If the compost is withdrawn every six months:

$$Vs_{ac} = \frac{Ms_{ac}}{\delta s_{ac}} = \frac{1887.0}{0.74} = 2550.0 \text{ cm}^{-3} \text{ per capita}$$

If the compost is withdrawn annually:

$$Vs_{ac} = \frac{Ms_{ac}}{\delta s_{ac}} = \frac{3774.1}{0.74} = 5100.0 \text{ cm}^{-3} \text{ per capita}$$

For designing purposes, it should be considered that withdrawal of sawdust would be conducted just before stabilized solids fill completely the pore space of sawdust matrix. Regarding that porosity of sawdust matrix is defined as $P = 1 - Vs/VT_m$, where P is the porosity, Vs is the volume of solids, and VT_m is the total volume of sawdust matrix; therefore, $VT_m > Vs_{ac}/(1 - P)$ to satisfy the condition stated before. Thus, the total volume for composting matrix (dried conditions) will be

If the compost is withdrawn every six months:

$$VT_m > Vs_{ac}/(1 - P) = 2550.0/(1 - 0.78) > 11591.0 \text{ cm}^{-3} \text{ (or 11.6 l) per capita}$$

If the compost is withdrawn annually:

$$VT_m > Vs_{ac}/(1 - P) = 5100.0/(1 - 0.78) > 23182.0 \text{ cm}^{-3} \text{ (or 23.2 l) per capita}$$

Thus, the volume and mass of dry sawdust required yields

If the compost is withdrawn every six months:

$$V_{ds} > VT_m - Vs_{ac} > 11591.0 - 2550 > 9041.0 \text{ cm}^{-3} \text{ (or 9.0 l) per capita}$$

$$M_{ds} > V_{ds} * \delta_s > 9041.0 * 0.19 > 1718.0 \text{ g (or 1.7 kg) per capita}$$

If the compost is withdrawn annually:

$$V_{ds} > VT_m - Vs_{ac} > 23182.0 – 5100.0 > 18082.0 \text{ cm}^{-3} \text{ (or 18.0 l) per capita}$$

$$M_{ds} > V_{ds} * \delta_s > 18082.0 * 0.19 > 3436.0 \text{ g (or 3.4 kg) per capita}$$

With these results, the F/S ratio, at which the composting reactor of the bio-toilet will work, is estimated as follows

If the compost is withdrawn every six months:

$$\frac{F}{S} = \frac{23.5}{1718.0} 100 = 1.4\,\%$$

If the compost is withdrawn annually:

$$\frac{F}{S} = \frac{23.5}{3436.0} 100 = 0.7\,\%$$

As seen, the F/S ratio is very low and within the range in which organic loading causes no limitations to the biodegradation process (Lopez Zavala et al., 2005). Consequently F/S ratio does not govern the design of the composting reactor.

Because the compost matrix will also contain water, the total bulk volume of compost matrix (VT_b) can be estimated as follows

$$VTb > VT_m + Vw; \quad Vw = \frac{W(Ms_{ac} + M_{ds})}{\delta_w}$$

where W is the moisture content (in g g^{-1}) and δ_ω is the water density.

Thus, the total bulk volume of compost matrix (VT_b) for a 60% (or 1.5 g g^{-1}) moisture content yields

If the compost is withdrawn every six months:

$$VT_b > VT_m + Vw > 11591.0 + 5408.0 > 16999.0 \text{ cm}^{-3} \text{ (or 17.0 l) per capita}$$

If the compost is withdrawn annually:

$$VT_b > VT_m + Vw > 23182.0 + 10816.0 > 33998.0 \text{ cm}^{-3} \text{ (or 34.0 l) per capita}$$

Using these values and the drying surface determined above, the thickness of the composting matrix (regarding a rectangular reactor) at the time of withdrawing the compost (H_s) is

If the compost is withdrawn every six months:

$$H_s > \frac{VT_b}{A} = \frac{16999.0}{643.0} = 26.5 \text{ cm}$$

If the compost is withdrawn annually:

$$H_s > \frac{VT_b}{A} = \frac{33998.0}{643.0} = 53.0 \text{ cm}$$

These dimensions were estimated regarding that no mixing is conducted. Therefore, the shape of the mixing mechanism or the mixing system may affect such dimensions. In addition, free space over the compost matrix surface for air circulation will also contribute with the total depth of the composting reactor. 10 cm may be reasonable. Thus the total depth of the reactor would be

If the compost is withdrawn every six months:

$$HT > H_s + H_f > 26.5 + 10 > 36.5 \text{ cm}$$

If the compost is withdrawn annually:

$$HT > H_s + H_f > 53.0 + 10 = 63.0 \text{ cm}$$

Similar analysis can be conducted for designing the composting reactor of the bio-toilet for more than one person.

Mixing will enhance the drying process; consequently, it may be thought that dimensions of the composting reactor may be reduced. However, because effect of mixing in drying process is difficult to evaluate with precision, mixing may result more important for operation rather than for design purposes. Thus, mixing effect was not regarded in the design procedure. In addition, in this study the shape of the composting reactor is considered to be parallelepiped, however, the current configuration is a semicircle in the bottom due to the shape of the mixing mechanism utilized. The dimensions here determined correspond to non-mixing conditions; therefore these may change depending on the type and shape of the mixing mechanism.

6. Conclusions

Criteria for the proper design and operation of the composting reactor of the bio-toilet system were established. Establishment of operation criteria led to the formulation of an operation scheme where three main zones are distinguished: *i)* "green zone", where the best composting performance is expected; *ii)* "yellow zone", where biodegradation can be conducted but performance is not the most efficient; and *iii)* other zones, where operation of the bio-toilet is not recommended because odor problems and human health risk will develop, or in the worst case, biodegradation of feces will not occur. The operation criteria can be summarized as follows:

a) The composting reactor should be operated at a moisture level near to 60%, or a little higher, but avoiding values near or higher than 65% to ensure high performance on biodegradation of feces, to avoid problems of odors and anaerobic emissions, and to reduce necessities of maintenance and services associated with sawdust replacement. In this respect, the critical moisture content may be used as reference parameter. Moisture contents lower than 50% should be avoided to ensure proper environment for microorganisms and consequently faster and complete stabilization of organic matter contained in feces.

b) Composting process should be conducted within the thermophilic range of temperatures, nearly to 60oC, to enhance biodegradability and biodegradation of feces, to inhibit and kill pathogenic microorganisms, and to enhance drying rates. Temperatures nearly to 70oC will kill both pathogenic and useful microorganisms. Lower temperatures will slow the decomposition process.

c) Mixing should be conducted to enhance drying rates and oxygen availability, and to improve the temperature distribution in the composting reactor and consequently pathogen killing effect. In order to reduce the compost withdrawal infection risk to an acceptable level (1x10-4 per year) mixing frequency should be i) 20 times per day during 2 days or ii) 15 times per day during 3 days after the last using-event of the bio-toilet in current operating bio-toilet.

d) Low pH (6-7) should be kept in the composting reactor of the bio-toilet system to ameliorate the high nitrogen losses in the form of NH3 volatilization. Alternative methods to conserve nitrogen in the sawdust matrix, for instance mineralization of NH4 in the form of struvite crystals, should be found due to high salinity, especially high concentrations of Cl, seems to be an inhibitory factor for the nitrification process in the composting reactor.

e) In the practice, continuous monitoring of the composting process and manipulation of the temperature controller of the system, mixing frequency, and the water amount for cleaning purposes should be conducted for keeping optimum temperature and moisture conditions in the composting reactor.

For the design of the composting reactor, the following criteria was established:

a) Size of the system was determined regarding the critical hourly water loading due to contributions of urine and water contained in feces. Water for cleaning purposes was considered negligible. Critical water loading resulted to be 208 g/capita and must be evaporated in a critical drying time of 3 hours to allow changing the moisture content within the range 50 to 60%.

b) Average drying rates were estimated based on drying tests conducted at recommended home temperature and moisture contents of air, 25^{o}C and 50 and 65% relative moisture, respectively. Temperature of the heating system of the composting reactor should be set at 60^{o}C to accelerate biodegradation reactions, to inhibit pathogens and to enhance evaporation rates.

c) Organic loading (F/S) due to feces contribution was revised for the dimensions already determined. Toilet paper was considered to be part of the sawdust matrix because its low degradability. Very low organic loads (F/S = 0.7 – 1.4%) characterized the system. Therefore, F/S ratio does not govern the design of the composting reactor.

d) Mixing frequency was not regarded for design purposes because its effect on drying rates has not been studied yet. However, mixing will enhance the drying process, consequently it acts as a "safety factor" to avoid undesired high moisture content.

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