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Original Research

Reutilization of Cornstalk as Matrix in Bio-Toilet

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Abstract

Sawdust is the most popular matrix used in bio-toilets, but the wood resource is scarce in many countries. The aim of our research is to explore the possibility to select cornstalks as alternative matrix in bio-toilets. The experiments were conducted to compare the biodegradation effects of feces mixed with sawdust and cornstalk by monitoring the main physical and chemical parameters. In both tests, temperature, moisture content, and pH were all maintained within a feasible range during biodegradation. The weight reduction was very remarkable, and TN, TP, and TK all significantly increased (although the loss of NH_3-N occurred). These results indicated the feasibility to use cornstalks as a bio-toilet matrix, which provides an effective way to reutilize agricultural waste and helps to popularize the application of bio-toilets.

Keywords: cornstalk, sawdust, matrix, biodegradation, bio-toilet

Introduction

Bio-toilet is the name of a dry toilet or composting toilet that uses sawdust as a bulky matrix for bioconversion of human excreta into compost, which can be used either as organic fertilizer rich in N, P, and K, or as a soil conditioner [1-3]. Composting toilet wastes in the bio-toilet system is a biological process that is affected by several factors such as type and quantity of microorganisms, availability and degradability of substrate, availability of nutrients (N, P, K, and others), and environmental conditions (temperature, moisture content, oxygen availability and pH) [4]. Any changes in these factors are interdependent, a change in one parameter can often result in changes in others [5-7].

Sawdust is the most popular matrix used in bio-composting of different materials such as pig manure and sewage sludge [1, 8-14]. Sawdust contains useful characters, for instance providing a suitable balance of water and air retention for aerobic biodegradation and tolerance to physical friction and biochemical reaction [15]. It also works as a carbon source for microorganisms [16].

Other matrices such as leaves [16], cornstalks [17], straw [18-20], and thredded papper [21] have been reported in bio-composting. Mccartney and Hongtu simulated the free air space of different composting systems and concluded that leaves should not be used as a bulking agent, wood chips showed superior bulking properties, and straw showed intermediate bulking properties [22]. However, wood chips/sawdust is not always available because of the scarce wood resources of many countries or regions. Therefore, suitable alternatives are needed to further popularize the composting technique and the application of dry bio-toilet.

Cornstalk, the most abundant form of agriculture residue, is rich in organic matter with high C/N [17] and porosity [23], which is suitable for work as a bulking agent.

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Table 1. Properties of the materials (%).

	Organic matter	θ	N	P_2O_5	K_2O	pH	C/N
Feces	77.75	79.12	1.09	0.40	0.22	8.26	18.19
Sawdust	98.79	34.10	0.09	0.05	0.43	6.64	396.64
Cornstraw	92.13	10.78	0.71	0.27	1.37	6.03	58.08

Moreover, cornstalks are much more plentiful in source areas – than sawdust, especially in countries lacking forest resources such as China and India. Nearly 284 million tons of cornstalks are produced per year worldwide [24]. Data from Ecorntech, Inc. shows that about 130 million tons of cornstalks are wasted per year, and most of them were directly burned or discarded. Thus, using cornstalks as a matrix provides an appropriate way to reutilize agricultural waste and is also beneficial from ecological and economic points of view. It also has been found that cornstalks are suitable for open co-composting with piggery wastewater [17]. In this study, we will investigate the possibility of selecting cornstalk as a substitute matrix in bio-toilets by comparing the biodegradation effects of feces mixed with cornstalk and sawdust, the most popularly bulking agent.

Materials and Methods

Experimental Device and Materials

The experimental device is the S-15 bio-toilet provided by JST (Japan Science and Technology Corporation). It mainly consists of a mixing and heating mechanism, feed and discharge opening, exhaust outlet, and a motor. The spiral blade (the mixer) lies longitudinally to the composting chamber. Except for the feed opening, a discharge opening is provided to extract the compost. A motor driving the mixer and heating mechanism is set at the end of the reactor (Fig. 1).

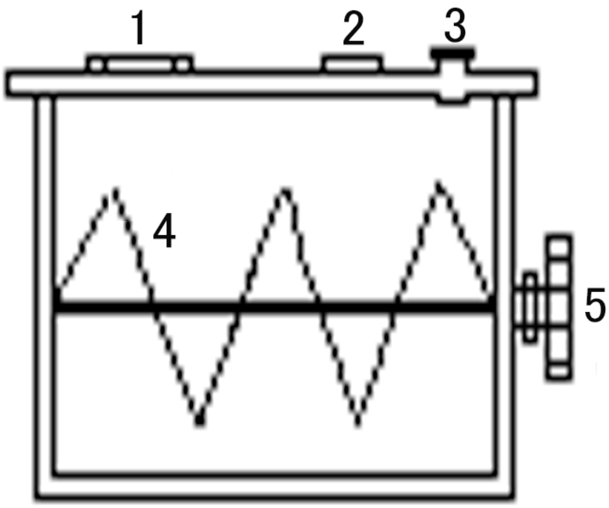

Fig. 1 Components of the experimental device (1 – feed opening, 2 – discharge opening, 3 – exhaust outlet, 4 – mixing mechanism, 5 – motor).

After feeding, the only operation is to push a button that activates the mixer to incorporate the air and feces into the matrix, and the mixing mechanism will operate periodically.

The cattle feces (mixture of manure and some urine) was obtained from the poultry industry in Changchun, China. Populus Tomentosa sawdust (granularity>0.84 mm) was purchased from a sawmill, and the cornstalks (1-2 cm long) were collected from Nong'an County. The properties of the materials are summarized in Table 1.

Tests Design

Tests for two kinds of matrix, sawdust, and cornstalk were conducted. Both experiments were performed for 45 days, and the initial moisture content (θ) was adjusted to about 60% by adding distilled water. The composting bioreactor of bio-toilet systems in practice is usually operated under organic loading near the feces/sawdust ratio of 10% on a dry basis [4]. In our research, 5 kg of matrix was added to the reactor and 2.5 kg of fresh feces was fed per day. The organic loading for feces/matrix ratio is 11.7% and 15.8% for cornstalk and sawdust, respectively. Since the feces was fed at 9 every morning, the mixer only worked from 9 to 18 every day by manual control. Feeding was stopped when the C/N ratio was less than 20:1 (on the 35^{th} day), the compost was kept in the reactor for another 10 days. Then it was withdrawn and weighed.

During the tests, temperature (Tm), moisture content (θ), organic matter (OM), pH, total carbon (TC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), C/N ratio, and weight reduction (R) were monitored as follows:

- Tm: The temperature of the compost was monitored at a depth of 0.2 m below the surface of the composting mixture at 9, 14, and 18 every day, and was averaged.
- θ: Solid samples were taken from different parts of the composting mixture at 0.2 m below the surface of composting mixture before feeding every morning. The samples were mixed uniformly and θ were gravimetrically measured by oven-drying the samples at 103ºC for 24 h.
- pH: 5 g of the wet sample collected as above was stirred vigorously in 30 ml distilled water for 3 min and allowed to stand for 20 min. Then the liquid was used to determine pH with a pH meter.
- OM: 1 g of the oven-dried samples was burned to constant weight at 600ºC in a muffle furnace for 24 h, and the OM was then determined.

- TN in the compost was determined by the Kjeldahl method, TC was determined with a VrioEL elemental analyzer, the C/N ratio was then calculated. To determine the total contents of P and K, the composting mixtures were first digested with nitric-perchloric acid, and then the TP was determined with inductively coupled plasma atomic emission spectrometry, TK was determined with a Varian 220FS atomic absorption spectrometer with graphite furnace. TP and TK were expressed as the percentage of P_2O_5 and K_2O, respectively.

R was calculated based on the following formula:

$$R = \frac{Q - S}{Q} \times 100\ \%$$

...where Q – total quantity added into the system, S – weight of residue.

Statistical Analysis

Statistical analysis was performed using SPSS 13.0. The data obtained from the experiments were subjected to one-way analysis of variance to determine the differences in the above papameters between the two tests, and the significance was concluded at p<0.05.

Results and Discussion

Evolution of Environmental Parameters

Temperature (Tm)

Tm is one of the most important factors affecting microbial growth and biological reactions. It can exert an effect on biological reactions in two ways: by influencing the rates of enzymatically catalyzed reactions and by affecting the rate of substrate diffusion to the cells. The change of Tm reflects the microorganism activity, and the microorganism is most active at 55-60ºC [25-28].

The heating mechanism in this biotoilet can keep the Tm of the reactor around 40ºC, but it will stop working when Tm further increases. Therefore, the change of Tm in our research was mostly due to the change of microbial activity and periodic mixing, since the Tm kept above 40ºC during the experimental period. In both tests, Tm followed the same trend. It increased to above 60ºC at the first few days due to the increase of microbial activity, and then fluctuated around 55ºC until day 35. After stopping feeding, Tm dropped gradually to below 50ºC (Fig. 2). This was similar to both the evolution trend and fluctuation range of Tm during the co-composting of pig manure [14] and human feces [29]. For batch composting, when Tm rose to the highest value it fell rapidly [29]. In this study, the feces was fed daily for 35 days (i.e. the nutrient was continously provided for microorganism), thus the Tm fluctuated at a high level (around 55ºC) for a longer period of time. Overall, no statistically significant difference was found between the Tm of two tests, although Tm peaked at different times in the two tests: 68ºC on the 10th day for sawdust matrix and 62ºC on the 13th day for cornstalk matrix.

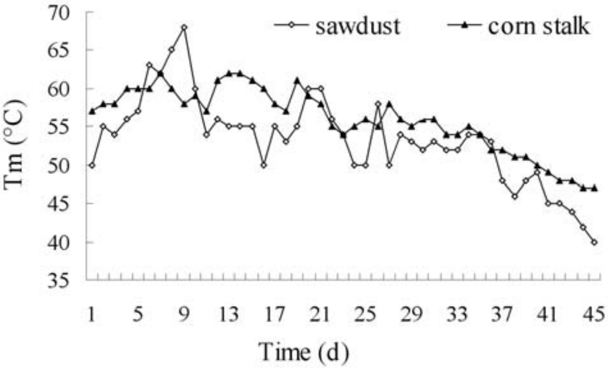

Fig. 2. Evolution of temperature (Tm) during the tests.

Suitable Tm is necessary to keep the biodegradation process stable and to make the compost harmless. According to the U.S. Environmental Protection Agency, the pathogeny organisms can be killed effectively if the Tm is over 55ºC for 3 days. It was also proven that heat generated by bacteria decomposting organic matter is apt to deactivate pathogens derived from the intestinal tract of humans [30, 31]. In our tests, the Tm ranged from 50 to 65ºC during the feeding time without any control, which will ensure the harmlessness of compost.

Moisture Content (θ)

θ is another important factor in microbial growth and biological reactions. The role of moisture in biodegradation is to participate in the metabolism of organism and to regulate the Tm by dissipating the heat through evaporation [32]. In addition, water is the key ingredient that transports substances within the composting matrix and makes the nutrients physically and chemically accessible to the microbes [33]. The optimum moisture content represents a tradeoff between moisture requirements of microorganisms and their simultaneous need for adequate oxygen supply [6]. Low moisture contents (40-50%) ensure aerobic degradation, but the nutrients are no longer in an aqueous medium and not easily available to the microorganisms; whereas high moisture levels (≥ 64%) cause anaerobic decomposition that generates odor and the emmision of aneaerobic products and induce matrix deterioration. Keeping moisture content near 60% or a little higher ensures optimum performance of the biotoilet system [5, 33]. In our study, the θ of feces reached 77.75%, but the θ of sawdust and cornstalk is relatively low (34.10% and 10.78%, respectively). Thus, distilled water was added to regulate the initial θ of composting mixture.

Fig. 3 showed the evolution of θ. On the first few days, much water rapidly was lost through evaporation because of the high porosity of the matrix, the increase of Tm and the periodic mixing, the water produced through the decomposition of organic matter and the added water by feeding of fresh feces was not enough to compensate for the

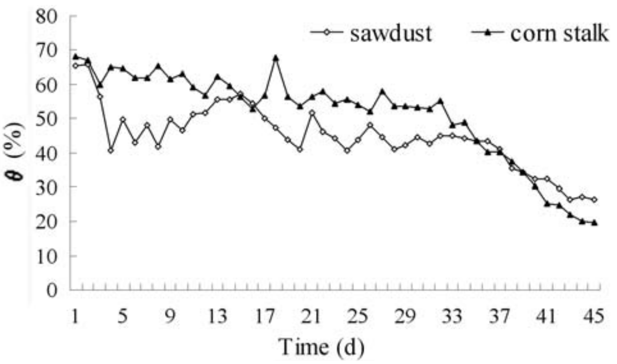

Fig. 3. Evolution of moisture content (θ) during the tests.

water loss. Therefore, θ reduced obviously during the first 3 or 4 days for the cornstalk and sawdust matrices, respectively. Subsequently, the water production through biodegradation enhanced and maintained at a high level along with the increase of microbial activity, which further made up for the water loss and kept θ at a certain range, 43.16-67.89% (average 56.93%) for the cornstak matrix and 40.76-57.02% (avarage 48.03%) for the sawdust matrix from day 4 to the end of the feeding period. Relatively large fluctuation was observed on some days, possibly because the feces was not mixed uniformly before feeding, which induced the variable θ of feces. Overall, θ met the requirements of the reseanable biodegradation rate of feces. Moreover, the θ in biodegradation with sawdust matrix is lower than that with cornstalk matrix during the active decomposing period, and a statistically significant difference was observed between them. This may be caused by the higher porosity of sawdust than cornstalk.

During the maturation stage after stopping feeding, no water was added into the system and the water generated by biodegradation was significantly reduced due to the decline of microbial activity, thus a rapid drop of θ was detected although evaporation, which also decreased, along with low Tm and porosity.

pH

The pH can also influence microbial growth and biological reactions. The suitable pH for a microorganism is 6.0-8.5 and some organisms can live outside this pH range [3]. In the composting process using a liquid medium, the optimum pH ranges for the degradation of proteins and glucose are 7-8 and 6-9, respectively [34]. Low pH may inhibit the activity of microorganisms, but a pH increase will stimulate the nitrogen losses because NH_3 will flow into the air when pH is over 7.0.

In practical operation of composting systems, very little evidence exists that pH should be manually adjusted for improving biodegradation rates [4]. Our results showed that pH slightly increased and reached the maximum value (9.24) on the 40th day for the cornstak matrix (Fig. 4), which was due to the accumulation of ammonia generated by the ammonification of organic nitrogen by microbial activity. Then a moderate decline followed, and this response might be due to the further volatilization of ammonium and less production of ammonia caused by the low microbial activity with limited oxygen availability. Moreover, synthesis of new organic acids and production of phenolic compounds in the late period of composting might also contribute to this response [35]. In contrast, the decrease of pH with the sawdust matrix began much earlier (on 28th day) and it then fluctuated around 8.3 in the last 15 days. However, the rapid decrease of pH from day 28 is hard to explain.

Evolution of OM

OM biodegradation affects weight reduction during composting. Insufficient OM may inhibit the microbial activity, thus the heat produced during biodegradation cannot maintain Tm at a high level and the compost efficiency will be very low. On the other hand, excessive OM can badly influence the aeration and oxygen availability, causing anaerobic degradation and odor. It was found that the suitable OM was 40-60% for composting of garbage [36].

As shown in Fig. 5, the biotoilet performed organic degradation well under the aerobic mesophilic conditions. During the composting process OM decreased over time, and this fall of OM can be greatly attributed to the mineralization of the OM from feces. One portion of the consumed OM was oxidized to provide energy, i.e. a great amount of OM was decomposed to CO_2 [4, 28] and then scattered to air through volatilization. The remainder of the substrate molecules were reorganized into new cell mass [4]. It should be noted that the OM from sawdust are formed of a

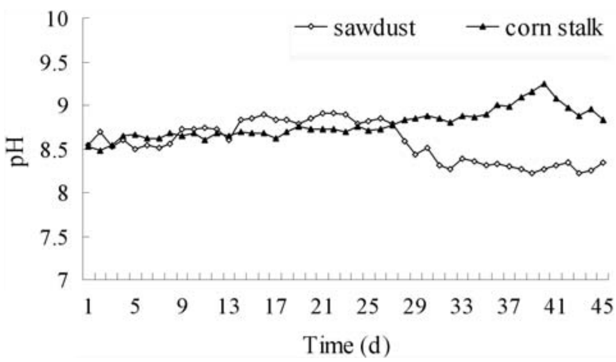

Fig. 4. Evolution of pH during the tests.

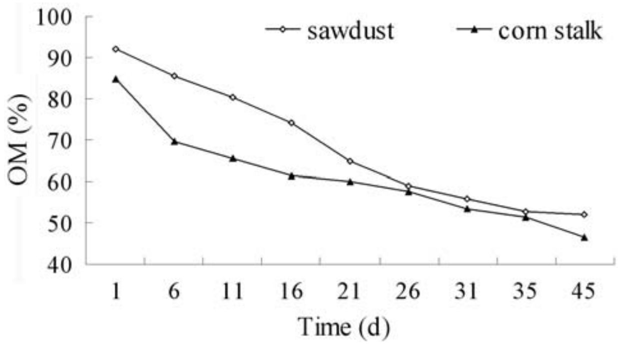

Fig. 5. The change of organic matter (OM) during the tests.

more structured fraction less susceptible to microorganism attack [37]. Therefore, the matrix was degraded to a very low extent [38, 39], which explained the reason why the matrix can be used for a long period of time. Moreover, our results showed that the mineralization rate of OM was significantly higher for cornstalk matrix during the first 21 days, while the final OM is a bit higher for sawdust matrix, which might be explained by the high content of lignin and cellulose, which is difficult to be degraded in the sawdust [24].

Evolution of C/N Ratio

C/N is one of the most important factors affecting compost quality. C/N>40:1 will lead to a decrease of biodegradation rate, and C/N≤20:1 will lead to more loss of nitrogen and lower fertilizer efficiency [38, 40, 41]. The optimum C/N for composting is considered 25-30 [38]. The C/N of sawdust and cornstalk is 396.64 and 58.08, respectively, which is much higher than that of feces (18.19), thus the initial C/N of the composting mixture was very high (51.82 and 143.68 for sawdust and cornstalk, respectively). Theoretically, the high C/N will inhibit microbial activity, but the reliable carbon was mainly provided by the feces [37], which is much lower than the total carbon in the mixture. Therefore, microbial activity was not inhibited by the high initial C/N, and it was kept effective in biodegradation.

It has been shown that the nitrogen loss (60.2% and 51.3% for sawdust and cornstalks, respectively) was lower than the carbon loss (66.4% and 72.9% for sawdust and cornstalks, respectively) during composting of feces in our research, which was in accordance with the findings of Hotta et al. [15] and Vuorinen and Saharinen [20]. Therefore, the C/N decreased with time during the active composting as shown in Fig. 6. The low C/N ratio is considered one of the parameters for estimating compost maturity and stability [42], and it can illustrate the success of the composting process in producing a final product similar to soil organic matter [43]. In our tests, the final C/N of the compost was reduced to 13.78 and 14.11 for sawdust and cornstalks, respectively, which was similar to the C/N of soil humus (typically 10 to 12) [44].

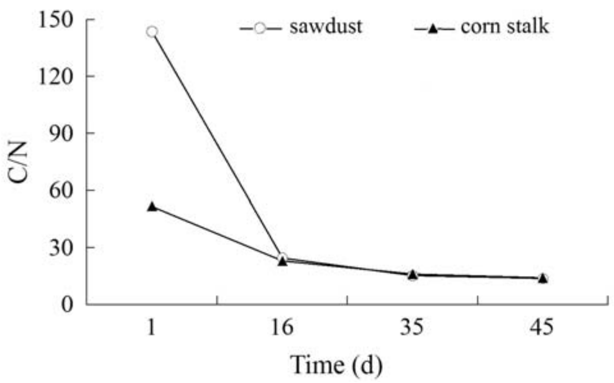

Fig. 6. The change of C/N during the tests.

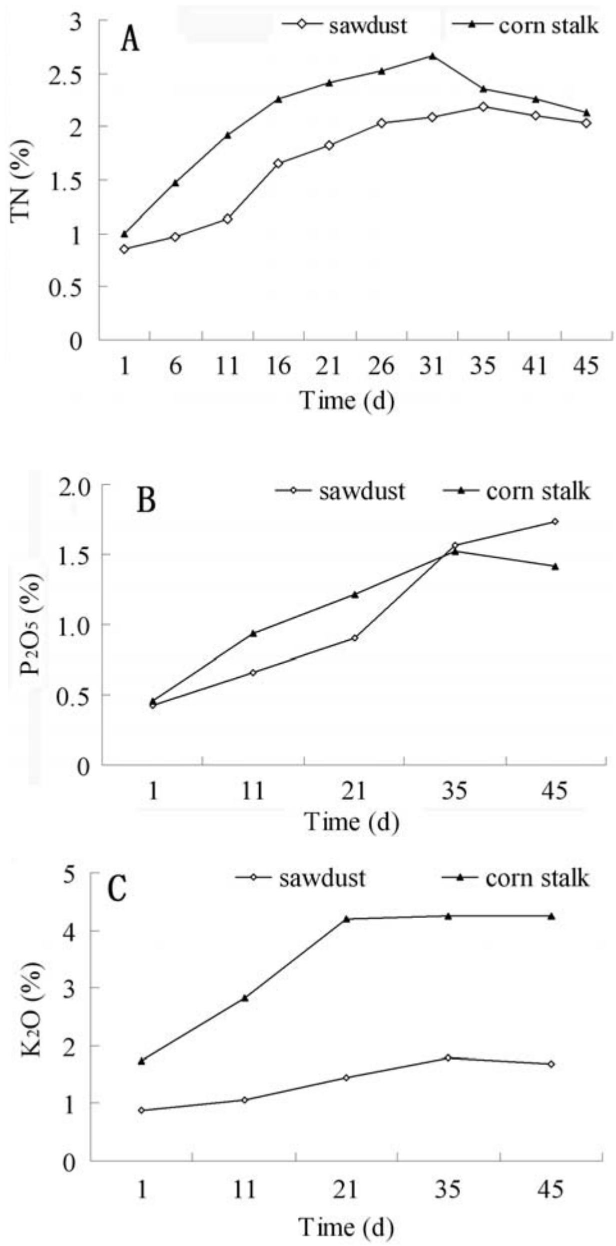

Fig. 7. The change of nutrients during the tests.

Nutrient Analysis during the Tests

During the composting process the organic nitrogen might be transformed to NH_4^+-N through ammonification, and then evaporated as NH_3 at high temperature or high pH. In our tests, although some nitrogen was lost through the evaporation of NH_3 and the denitrification of NO_3-N, the TN increased in the forepart of the experimental period (Fig. 7A). The reasons include:

(1) Nitrogen was continously added into the system by feeding fresh cattle feces.
(2) The decomposition of OM and water evaporation all led to the decrease of dry solid [14].

In the last period, there was no nitrogen input and the total dry solid would not decrease greatly because of the low microbial activity, which accounted for the decrease of TN.

Table 2. Change of wet and dry weight in the tests.

Materials	Wet weight			Dry weight		
	Q (kg)	S (kg)	R (%)	Q (kg)	S (kg)	R (%)
Feces and Sawdust	92.5	23.0	75.14	21.48	14.02	34.73
Feces and Cornstalk	92.5	18.5	80.00	22.66	16.23	28.31

Moreover, TN of the material with cornstalk was higher than that with the sawdust matrix, which was due to the nitogen content of cornstalk (0.71%) and much higher than that of sawdust (0.09%) (Table 1), and the nitrogen loss with cornstak matrix (51.3%) is lower than that with the sawdust matrix (60.2%), as shown above.

We also found that the evolution of TN is consistent with the pH and Tm changes, because the volatilization of NH_3 occurred at a high pH and Tm. As shown in Figs. 2 and 4, Tm was kept at over 50ºC during the feeding period and the pH was maintained at a high level (>8.0) all along, which gave rise to nitrogen loss through the evaporation of NH_3. It has been reported that volatilization of ammonia is the main reason for the loss of TN [1, 40]. Since most nitrogen in the toilet waste is from urea [45], they are unstable in the sawdust matrix, especially when feces is mixed with urine [46]. Therefore, source separation of urine from feces would significantly change the CN balance in the biodegradation system and then improve nitrogen loss [15].

TP and TK moderately increased until the day 35 as shown in Figs. 7B and C. In contrast to N, P and K are more stable in physicochemical quality. They changed little or didn't change at all during biodegradation and so the continuous feeding was responsible for their steady rise during the feeding period. Afterward, their rise slowed or no obvious rise was observed because no input of P and K continued and the rate of weight reduction decreased due to low microbial activity. TK of the composting mixture in the experiment with cornstalk matrix is significantly higher than that with sawdust matrix, which was partly caused by the higher K content (1.37%) of cornstalk in comparison to that of sawdust (0.43%) (Table 1). However, the higher content of K in cornstalk could not induce such a significant difference, which meant that there are some other unknown reasons. Another point that can be noted is that the TK in the experiment with cornstalk matrix almost stopped growing since day 21 rather than at the end of the feeding period as shown in the other experiment with the sawdust matrix, which might be related to the low reduction rate of total weight caused by the decreased biodegradation rate during the latter period. Other as yet unclear reasons might also contribute to this result.

Weight Reduction (R)

It was once found that the degradation rate was nearly constant at a moisture content of 30%-80% on a wet-weight basis [47]. Lopez Zavala et al. also found a clear linear correlation between total solid (TS) reduction and organic loading, and the TS reduction was approximately 56% irrespective of the organic loading [1]. Similar results on the removel of TS (51%) were ovserved by Bai and Wang [48].

In our research, R was calculated by taking the difference between the total mass that was put into the biotoilet and the residual mass at the end of experiments. As shown in Table 2, R was very significant, at 75.14% and 80.00% on wet weight basis and 34.73% and 28.31% on dry weight basis for sawdust and cornstalk, respectively. These results are significantly lower than what was found in the batch tests [1, 48]. Except for continous feeding, the high organic loading for the whole composting process (feces/matrix ratio are 5.52 and 4.08 for sawdust and cornstalk, respectively) might partly explain the low R in our study.

The wet R with cornstalk matrix is a bit higher than that with sawdust matrix, which may be related to the greater loss of water during maturation stage, which might be caused by the low capability of cornstalks to shed water. However, the dry R with sawdust matrix is more remarkable, which may be expained by that the higher porosity of sawdust, provided the microorganism is a better aerobic environment.

Besides, an experiment carried out on Mount Fuji in Japan in summer 2000 showed that 250 L of sawdust matrix needs to be replaced once the large toilet is used 3,000 times. Thus, nearly 200 L sawdust will be saved per person per year, assuming that he or she excretes 6 times every day (including five times of urinate and one time of defecating). Therefore, expanding the use of cornstalk as an alternative matrix will greately contribute to wood saving.

Conclusions

Bio-toilet composting is a continuous thermophilic aerobic biodegradation process where the feces is treated, and its affordability depends greatly on the steady-operation of the system and its capacity to reduce and stabilize the organic matter contained in the feces [1]. In our research, the bio-toilet system could operate steadily and the monitoring of important parameters showed that it is feasible to choose cornstalk as a bio-toilet matrix. This measure will not only save the wood resource and reduce the cost of the bio-toilet, but also will reutilize agricultural wastes. Although these results were obtained in small-scale experiments, we believe that this could be extended to practical use if managed properly.

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