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Gas release and ventilation in a dry toilet – comparison between different models

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The aim of the study was to understand the composting process from the gas emissions in dry toilets. Two dry toilet models were used: Naturum, where urine is separated from the faecal matter; and Dual-layer dry toilet with a mixed composter. The measurement period of three months was divided into four sections, according to the adjustments of air ventilation and moisture content. The scope of the work was to evaluate the CO_2, H_2S, NH_3 and CH_4 emissions, temperature and relative humidity from composting. The moisture content of the compost was improved by reducing air ventilation. In Dual-layer dry toilet gas emissions followed the same pattern as the moisture content. The composting performance of Naturum tended to be better than in Daul-layer dry toilet. The faecal nitrogen loss of Naturum was also smaller than in Dual-layer dry toilet. For Dual-layer dry-toilet, the cumulative emissions were 2.9±28 mg of H_2S, 2508±20g for CH_4, and in last three periods 12g±193mg for NH_3. In Naturum, only the H_2S emissions could be quantified, being about 418±148mg. A moisture content of 35-40%, and air ventilation rate of 5L/s for Dual-layer dry toilet and 2-3L/s for Naturum are recommended for a proper composting.

Keywords: *air ventilation, dry toilet, moisture, NH_3, composting*

Introduction

Aerobic composting is the most favorable method for treating the human waste (feces and urine) in a dry toilet system. The end-product of the aerobic degradation of feces is ann organic fertilizer or soil enrichment material, rich in N, P and K. The quality of compost depends on the amount of nutrients left, especially N, which is an essential element for plant growth. However, substantial quantities of N can be lost as via NH_3 volatilization when organic matter is actively decomposed under different conditions (Szanto G.L. et al., 2006; Sanchez-Monedero, 2000; Hotta and Funamizu, 2006b).

As it has be indicated by plentiful studies, for a dry toilet to function properly the proper control of water balance, temperature, C/N ratio as well as pH of the toilet compost is needed. These parameters affect directly or indirectly the biodegradation performance and the quality of the resulting compost (Jenkins, 1999; Lopez Zavala and Funamizu, 2006.).

There have been numerous laboratory-scale studies on the aerobic composting of human feces, in most of these studies however only the effects of individual factors were examined, while interactions among these factors were seldom addressed, especially on a real scale. Although the theories and the concepts of composting process for different kinds of dry toilet are mostly the same, the individual properties of particular dry toilet type can have their special characters during composting.

The objective of this study was to examine the gas emissions from the humanure composting in real dry toilets, using an automatic gas control system and manual gas detector. The results of this study can help to understand the humanure composting process and evaluate the optimum conditions for it. These can be further used to improve the toilet design based on operation performance and compost quality.

Two dry toilets with different capacities were chosen to be the study targets; Naturum is a urine-diverting toilet with 30L composting capacity and Dual-layer dry toilet is a urine-mixed system with 400L composter. After a year of usage, both toilets seemed to have poor composting performance under a visual study because of the significant air ventilations, leading to heat and moisture losses. The moisture contents of the composts from both toilets were relatively low, about 40% for Naturum, and only about 20% for Dual-layer dry toilet. The low moisture content probably resulted in conditions that were too dry for most of bacteria.

Methods

Both of the two toilets used in this study were manufactured by a Finnish Company BIOLAN Oy., which sells wide range of dry toilet, compost and water purifying related products and services. The two study toilets are Dual-layer dry toilet (Picture 2) and Naturum (Picture 3). The former applies to urine-mixed dry toilet (UMDT), and latter to urine-diverting dry toilet (UDDT). Both toilets were installed indoors and got used in the laboratory building at TAMK in 2009. Neither of them has been emptied yet, excluding the separated urine tank of Naturum.

The Dual-layer dry toilet is a urine-mixed composting toilet (UMDT), in which the urine is required to provide essential moisture and nitrogen to the compost due to limited amount of users (about 15 using times/month). BIOLAN peat was employed to be the bulking material for balancing the C/N ratio. The toilet seat is connected with the 400L composter underneath. The outer shell was made of rodent and scavenger proof polyethylene with three bed temperature monitors which were located at different height levels. There are also few air intake holes connected with inner air distribution system and the whole composter is surrounded by insulator, to maintain temperature. At the bottom part of the composter, there is a hole reserved to receive the excess liquid which comes out from the composter. Besides the seat opening, there are also two open windows locating at the top and the bottom part of the composter (Picture 1). Because of its large composting capacity, this passive and low-temperature composting with low-maintenance requirement is expected to yield relatively pathogen-free compost after a period of time.

Picture 1. Dual-layer dry toilet composter (right) with Naturum urine tank (left) and gas control system (back)

Picture 2. Naturum dry toilet

The Naturum dry toilet is a urine-diverting dry toilet (UDDT) (Picture 2). Its key part is the rotary drum composter, which is set up right at the back of the toilet, and there is an emptying container in it as well. It requires no electricity, water or chemicals to operate. It is designed for four persons in continuous use, and own-designed capacity for liquids with a separated urine container. Operation of Naturum is based on the composting of solid waste and separation of liquid in the toilet seat. When solid waste, including toilet paper and bulking material, drops into the drum through the seat opening, it is transferred to the composter by depressing the foot pedal manually a few times. The fresh waste will be covered to avoid creating any odour, and in the meantime, the compost is mixed by rotating the drum. The excess compost gradually drops into the emptying receptacle with the growing mass, and then the amount of the mass in the drum remains constant. User can empty the compost by taking out the emptying bucket. The urine is diverted into the urine tank at the basement, through the urine hole at the toilet bowl. It is recommended to 'flush' the urine with small amount of water after every single use to prevent crystallization of struvite. In Naturum, a specific bulking material is used, its required amount is only half of the normal ground peat, which is normally used in dry toilet. According to own test, the Naturum bulking material has about 97% of moisture content. As in most bulking materials, the granule can be completely decomposed in the compost (Biolan Oy., 2010).

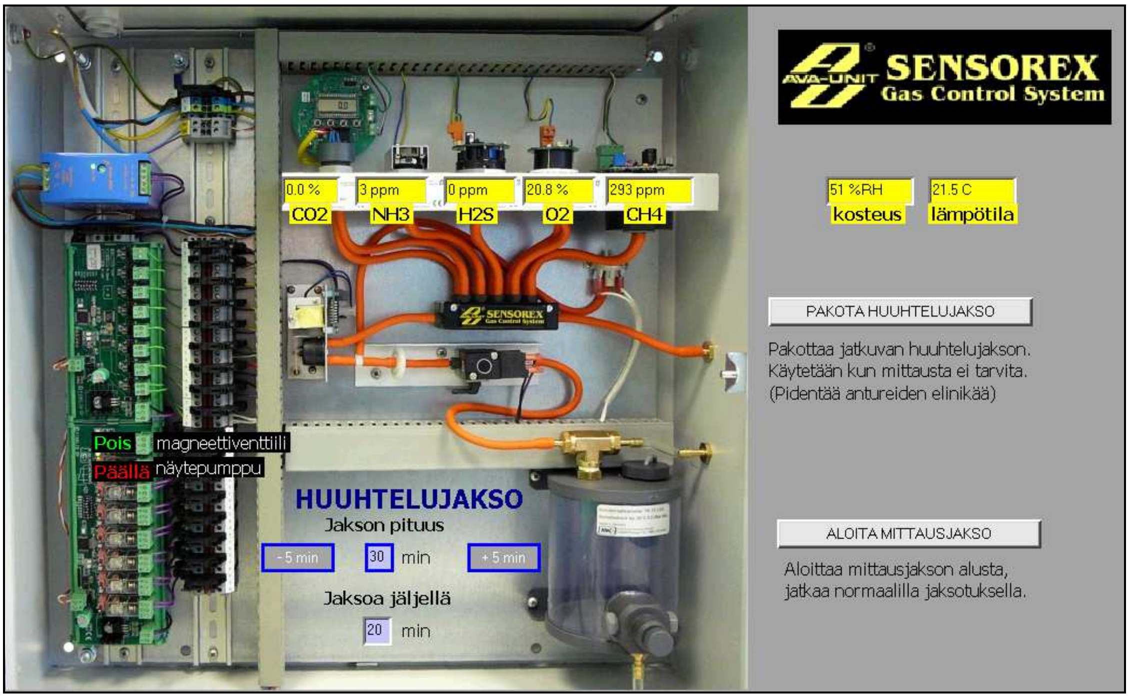
The whole study and the measurement period were divided into four periods, according to the adjustment of air ventilation and moisture content (Table 1). The first period worked as a ‘blank sample’ without any changes or modifications, so to give a reference for comparing the results. The strong air ventilation dried out the compost. In the second period the air ventilation was fixed to raise the relative humidity (RH) of the composting environments for both dry toilets. At the middle of the second period, compost samples from both two dry toilets were taken for total Kjeldahl nitrogen (TKN) test. In the third period, a week time was used to increase the moisture content of the compost by adding tap water from time to time. In the last period, the dry toilets were closed for observation and monitoring.

TABLE 1. Time table of the measurement periods

Period	Duration	Date	Note
1	3 Weeks (Week 1-3)	16.1-6.3.2012	Strong air ventilation 6.3.2012 Calibration for sensors
2	4 Weeks (Week 4-7)	7.3-3.4.2012	Reduction of air ventilation 1st TKN Test
3	1 Week (Week 8)	4.4-12.4.2012	Increase moisture content of compost
4	2 Weeks (Week 9-10)	13.4-27.4.2012	Closing of dry toilet

The gas control system used in the case of Dual Layer dry toilet , provided by a Finnish company Sensorex Oy., is an automatic gas sensor system, which aims to detect the gases emitted from the compost inside the composter of Dual-layer dry toilet only. The electrochemical measuring system is equipped with five independent gas sensors, which are O_2 (% volumic), NH_3 (ppm volumic), H_2S (ppm volumic), CO_2 (% volumic), CH_4 (ppm volumic), as well as a combine sensor of RH (%) and temperature (℃).System control and data review can be done through an intranet program that saves the measurement data. In the control panel, the measuring period and rinsing period can be adjusted according to the need (Picture 3). The measurement period was set to be half an hour, meaning that gas sample is taken in every 30 minutes continuously for every day. Also, there is a history review to check out the old data according to the entered time period and number of result for each sensor, and the data can be shown in a table or in a graph. In addition, the chosen data can be exported out into the format of Microsoft Excel for further use.

Manual gas measurement in the Naturun toilet was done by using a mobile gas detector MX6iBird, with sampling pump. It can detect and measure oxygen (O_2), ammonia (NH_3), Hydrogen sulfide (H_2S), combustible gases (LEL/CH_4), as well as carbon dioxide (CO_2). IR Methane sensors’ reading is not to be used for methane (CH_4) concentration below 5% in air. The gas measurement of Naturum was basically done by using this mobile gas detector, following the time table of Table 1. The measurements were taken 2-3 times a week and the gas samples were directly taken from the emptying bucket of Naturum. Air flow measurements were done by using manual ventilation meter. In Naturum, there was a hole prepared on the ventilation pipe that the sensor can be put inside. For Dual-layer dry toilet, measurements were taken from both ventilation pipes, and inside the composter. The measurements were taken in the first and second period to provide data for air ventilation adjustment. Air flow measurements were done by using VelociCalc 9555 Multi-Function Ventilation Meter with two different probes; thermoanemometer probe model for duet measurement and rotating vane probe model for open air cone. The former applied to the measurement of the ventilation pipes of Naturum and Dual-layer dry toilet and the latter was used to measure the air flow inside the composter of dual-layer dry toilet. The determination of moisture content of the compost was done according to the Finnish Standard SFS-EN 13040, with moisture analyser XM 60. Moisture content of the composts was kept control and measured once in a while regarding the ventilation change and the moisture adjusting in third period. In order to raise the moisture content for dual-layer dry toilet, additional tap water, 8 litres in total, was added from time to time to the composter to achieve 50-60% of moisture content.



Picture 3. Control panel of Sensorex gas control system

The TN represents % measured organic nitrogen in the mass of the sample, including ammonia nitrogen (NH_3-N). The analysis was followed by European Standard SFS-EN 13342, to determine both the organic nitrogen and the ammonia nitrogen forms in the compost. Samples were taken from the upper and the bottom layers of the Dual-layer dry toilet, and from the emptying bucket of Naturum in the second period. The masses of the particular gases eliminated through ventilation were calculated by using the ideal gas law:
$nRT = pV$, where

n- number of moles [n] = mol/time
R- universal gas constant [R]= 0.0821 L*atm/(mol*K)
T- thermodynamic temperature, average temperature was taken into calculation [T] =K
P- pressure [p] = atm, 1atm was taken into calculations
V- volume of the gas [V] = L/time, calculated from average for each period of the sensor measurements, and aeration flow rate

For the assessments of the gas composition, average values of the gas emission measurements were calculated for each period and for each gas. For the approximations of the cumulative gas losses the standard errors of the means were also calculated. For statistical calculations Microsoft Excel was used to calculate the standard deviation. The calculated stand errors of the means were applied also to the ideal gas law, in order to estimate the errors of the amount of gases.

Results and Discussion

The air flow measurement data is shown in Table 2. In Dual-layer dry toilet, the RH was remarkably increased by nearly 80% with the reduction of air flow and was kept over 40% on average for the rest of the observation periods.

TABLE 2. Air ventilation adjustment details

Period	Air Flow		RH	Moisture Content
	Ventilation pipe(L/s)	Inside composter (m/s)	(%)	(%)
(a) Dual-layer dry-toilet				
1	30	5	24	20.49
2	5	0.5	43	30.05
3	5	0.5	43	35.32
4	5	0.5	48	28.13
(b) Naturum dry-toilet				
Period	Air Flow (L/s)	Moisture Content (%)		
1	4.5	40		
2	3	64		
3	3	77		
4	3	46		

In addition, the moisture content of the composts was improved with the increased RH, and it was further enhanced by 5% in the third period by adding extra 8L of tap water to the composter. In Naturum dry toilet, a high moisture content of compost was obtained immediately after the reduction of air ventilation, and it rose up to 77% in the third period. In the last period, moisture contents of the composts from both toilets declined again, although RH levels were almost remained.

Table 3 shows the average concentrations of gas emissions from each period for both toilets. The O_2 contents of the two toilets were kept at a constant level which was close to ambient (20.8%). Only traces of CO_2 were detected for Naturum, which was less than or close to atmospheric concentration 0.05% according to own measurements of MX6iBird gas detector. In Dual-layer dry toilet, the gas control system showed 0% concentration of CO_2, presenting no significant emissions. H_2S was detected from both toilets and it had the least emissions, whereas CH_4 was detected only in Dual-layer dry toilet and gave out the largest emissions among other gas measurements.

Table 3. Average gas emission concentrations

	Dual-layer Dry-toilet				Naturum			
Period	1	2	3	4	1	2	3	4
O_2 (%)	20.8	20.8	20.8	20.8	19.7	20.8	20.8	20.8
CO_2 (%)	0	0	0	0	0.02	0.2	0.25	0.12
H_2S (ppm)	0.14	1.15	0.14	0.15	0	0.38	0	0.25
NH_4 (ppm)	234	410	431	305	0	0	0	0
NH_3(ppm)	*Nil	8.8	9.9	5.0	(**Nil)			

*NH3 was not measured in the first period due to calibration accuracy

**MX iBird gas detector cannot measure NH_3

In order to compare the values, the concentrations of H_2S, CH_4 and NH_3 which were measured in ppm, were calculated as mg/s by taking the air flow factor into account. The results are given in Table 4.

Table 4. Gas emission rates

Period	Air Flow (L/s)	RH (%) (%)	Temperature (℃)	NH_3 (mg/s)	CH_4 (mg/s)	H_2S (mg/s)
(a) Dual-layer dry-toilet						
1	30	24.00%	22	Nil	0.46	5.9×10^{-4}
2	5	43.00%	22	3.1×10^{-3}	0.13	1×10^{-4}
3	5	43.00%	21	3.4×10^{-3}	0.14	9.7×10^{-5}
4	5	48.00%	21	1.7×10^{-3}	0.1	1×10^{-4}

(b) Naturum dry toilet

Period	Air Flow (L/s)	H_2S (mg/s)
1	4.5	0
2	3	1.25×10^{-4}
3	3	0
4	3	1.05×10^{-4}

The air temperature inside the composter of Dual-layer dry toilet remained constant at about 21^0C, which was similar to the Naturum dry toilet. The H_2S levels for both toilets had similar emission rates and generally remained very low during the course of composting. The highest H_2S emission was obtained from the Dual-layer dry toilet in the first period before the reduction of air ventilation. CH_4 was detected only in the dual-layer dry-toilet, and it was remarkably reduced by more than 70% in the second period with the reduction of air flow. In the last period, the lowest emission level (0.1 mg/s) was obtained. NH_3 emissions slightly increased in the third period when extra water was added to the compost but they came down to the lowest level at the end of the period, comparing with

other periods. In general, gas emission rates in the first period were higher than in the last period.
Forced ventilation supplies sufficient oxygen to compost, therefore we expected to have aerobic composting process in both toilets. In Dual-Layer toilet however the low CO_2 level inside the composter indicated that this system had anaerobic conditions. This was confirmed by the emission of CH_4 and H_2S (Table 3). Under anaerobic condition, the carbon from organic compounds is released mainly as CH_4. Oxygen is supplied mainly to the surface of the compost; therefore the layer of aerobic portion was limited. The middle compaction part of the compost suffered from lack of oxygen even though there were air intake holes on the composter. The compaction reduced aerobic degrading and lead to an increased presence of anaerobic regions, promoting emissions of CH_4 and H_2S. The air intake holes on the composters seemed to fail in handling this large quantity of compost mass.
In Naturum, there was no CH_4 detected, but there were H_2S emissions recorded from the manual gas detector in the second and fourth period (Table 1). Therefore in Naturum's compost anaerobic conditions might be reached from time to time or within some portions of the compost volume. The specially designed part of Naturum is the rotary drum composter which airs the compost every time when the foot handle is pressed. The design is useful in maintaining healthy compost. By turning the compost, oxygen availability is ensured. In addition, according to a previous finding, the scale of the compost also affects the volume of the anaerobic and aerobic portions (Fukumoto et al., 2003, Tanaka et al., 2009). The composting scale of Naturum is much smaller than that of the Dual-layer dry toilet and the smaller scale helped to reduce the volume of anaerobic portions. In the case of Dual-layer dry toilet, which handles higher compost volumes, it is possible that the volume of anaerobic portions will be enlarged with the increasing user frequency.
The cumulative emissions of the gases in the 3 month period were calculated with the data in Table 3. For Dual-layer dry toilet, the cumulative emissions in four periods are 2.9±28 mg of H_2S, 2508±20g for CH_4, and in last three periods 12g±193mg for NH_3. In Naturum, only the H_2S emissions could be quantified, being about 418±148mg.
The ventilation in the periods 2, 3 and 4 was constant, therefore we can assess the effect of moisture content on the gas emission. In Dual-layer dry toilet the gas emission rates of gases were high in general in the first period when the ventilation was at its maximum. Gas emissions dropped when the ventilation was reduced. CH_4 dropped more than 70% in the second period. In the rest of the measuring periods, the gas emissions followed the pattern of the moisture content. Gas emission rates tend to increase with increasing moisture content of compost. The 'anaerobic volume' in the compost of Dual-layer dry toilet might be enlarged with the increased moisture content, so as to give higher emission rates in CH_4 and H_2S. However, the moisture content difference of the compost from Dual-layer dry toilet in the three periods was rather small (about 7%). With respect to the gas emission variation with the variation of the compost humidity in the Naturum toilet, conclusions cannot be drawn, since the measured differences were very small. As a consequence, these findings should be treated with care. Longer measuring times and further studies are needed before drawing any final conclusions.

The air temperature in Naturum and Dual-layer dry toilet remained at a constant level of about 21°C. Mild composting temperature slows down the biodegradation rate of compost, decreasing the gas emission rate and quantity as compared with gas emission of thermophilic composting (Lopez Zavala et al., 2004). Having mild temperature and low level of CO_2 emission in Dual-layer dry toilet, the composting process is believed to be relatively slow without any rapid aerobic degradation. The biodegradation rate of organic matter is important in dry toilets because faeces and bulking material are added daily into the composter. In the Dual-layer dry toilet, the accumulation rate of faecal matter and bulking material might excess the degrading rate even though the capacity of compost is 400L if there are a lot of users. Consequently the cumulative layer might create a larger compaction which leads to more anaerobic gas emissions and also odour problems. For example, H_2S is an anaerobic gas which has foul sulphurous odour and it showed an emission relation with CH_4 in Dual-layer dry toilet. The large composting capacity provides a long curing period to ensure the safety net for pathogen destruction since human pathogens only have a limited life time outside the human body. However, longer storing time is needed to consider compost from UMCT as sterile, since urine is mixed with faeces, leading to possible persistence of viruses (Hotta. et al., 2007). It is, therefore, not safe to empty the composter if the compost is not sterile due to the slow biodegradation rate.

In Naturum, the biodegradation rate might be higher than in the Dual-layer dry toilet due to the higher moisture content of compost, encouraging microbial activity and permitting adequate oxygen supply. About 0.25% of CO_2 emission was recorded in the third period (Table 3), showing that aerobic composting process was taking place. Due to the limited composting capacity, the number of users needs to be restricted in order to avoid a high emptying frequency. In this study the issue did not impose a problem since there were only 2.5 using times/month in average.

During composting nitrogen is lost because of ammonification (Hotta and Funamizu, 2007; Bai and Wang, 2011, Lopez Zavala and Funamizu, 2006) . The prevention of NH_3 emission is important in order to keep N in the compost. In the case of the Dual-layer dry toilet, the NH_3 emission rate increased from the second period to the third period, but it dropped down nearly 50% in the last period along with the decreased moisture content. The reduction of NH_3 emission in the last period was believed to be caused by the acidic environment created by the anaerobic activity.

The TN value of Dual-layer dry toilet from the bottom and upper layer was about 1.41% and 0.89% respectively. Naturum contained similar concentrations as the lower part of Dual-layer dry toilet. The input nitrogen value of the Dual-layer dry toilet was higher than in the Naturum because of the urine input. TN in Naturum's compost had a similar value with the Dual-layer dry toilet's compost in the lower part. The compost from the upper part of Dual-layer dry toilet's composter only had half the amount of total nitrogen value. In other words, the Dual-layer system tends to have a greater nitrogen loss than Naturum. This is due to the hydrolysis of urea from urine that leads to formation of NH_3 (Hotta and Funamizu, 2006b). Over all, the TN value in both composts is less 3%, that is, from the fertilizing point of view, considered relatively low (Bueno et al., 2007).

Conclusions

Concentration levels of O_2 (20.8%) and air temperature (21°C) detected in both dry toilets were close to the ambient levels and stayed constant in the whole period. The highest CO_2 emission recorded from Naturum is about 0.25% in the third period. In Dual-layer dry toilet, CO_2 was not detected by the Sensorex gas control system in the whole period, indicating that the composter had anaerobic conditions which were confirmed by the emissions of CH_4 and H_2S. The biodegrading rate of Dual-layer dry-toilet is slower than Naturum because of the higher moisture content and the smaller composting scale. Naturum with UDDT system kept a higher nitrogen value than Dual-layer dry toilet with UMDT system, since there is less loss in nitrogen input.

From the results it can be concluded that the moisture content of the compost is successfully improved by reducing air ventilation. In the Dual-layer dry toilet, gas emission rates tend to increase with an increasing moisture content of compost. However, the moisture content difference of the compost from Dual-layer dry toilet in the three periods was rather small. With respect to the gas emission variation with the variation of the compost humidity in the Naturum toilet, we cannot draw any conclusion, since the measured differences were very small.

The recommended moisture content for both dry-toilets is about 35-40%, which maintains the microbial activities in compost and keeps gas emission rate still relatively low. Low moisture content (<30%) should be avoided by adding water. The current air ventilation rate of 5L/s for Dual-layer dry toilet and 2-3L/s for Naturum went well with the systems. Also, the composting performances can be improved if there are more users to keep a balanced C/N ratio in Naturum and to give moisture to Dual-layer dry toilet.

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